ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ88-278

PRESENT STATUS OF MANAGEMENT AND TECHNICAL PRACTICES ON ALLUVIAL FAN AREAS IN ARIZONA

State of the Art

Final Report

Prepared by:
Robert L. Ward
Consulting Engineer
706 North Gentry Circle
Mesa, Arizona 85203

November 1988

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Arizona Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names which may appear herein are cited only because they are considered essential to the objectives of the report. The U. S. Government and The State of Arizona do not endorse products or manufacturers.

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA-AZ88-278		

4. TITLE AND SUBTITLE	5. REPORT DATE
Present Status of Management and Technical Practices on Alluvial Fan Areas in Arizona	November 1988
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert L. Ward	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Robert L. Ward, Consulting Engineer, 706 North Gentry Circle, Mesa, Arizona 85203	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO. HPR-PL-1(31) Item 278
12. SPONSORING AGENCY NAME AND ADDRESS ARIZONA DEPARTMENT OF TRANSPORTATION, 206 S. 17TH AVENUE, PHOENIX, ARIZONA 85007	13. TYPE OF REPORT & PERIOD COVERED Draft Final Report July 1987 - November 1988
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

As assessment is made of alluvial fan flooding problems in the southwestern United States, with particular emphasis given to such problems as they presently exist in Arizona. A review is made of state-of-the-art technical procedures and floodplain management practices that are presently available for application to this environment. Application of National Flood Insurance Program (NFIP) criteria to highway planning and urbanization on alluvial fans is also discussed. An overview is presented reletive to current policy utilization by the Arizona Department of Transportation (ADOT) in planning highway projects to comply with NFIP criteria.

A secondary objective of the study consists of a review of the Corps of Engineers Regulatory Program (Section 404 of the Clean Water Act), as it is presently being applied to alluvial fan areas and ephameral washes in Arizona. Discussions examine the history of the "404" program and evaluate its impact on highway development in Arizona and explore clarification of such key terms as "ordinary high water mark" and "headwaters." ADOT's policy for compliance with "404" program criteria is also evaluated.

The report concludes with research recommendations that could enhance the ability to effectively manage the development of alluvial fans.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Alluvial fan, flooding, desert fluvial systems, National Flood Insurance Program, Section 404 of the Clean Water Act	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	256	

Table of Contents

Table of Figures

Table of Tables

1 INTRODUCTION

The arid and semiarid desert environments of the southwestern United States present a unique landscape comprised of fluvial systems that behave much differently from those found in more humid climates of the country. This difference in behavior is a function of such factors as short duration, high intensity rainfall, abrupt changes in topography, and a sparse vegetation community which creates the relatively bare surface conditions of desert soils. These factors combine to magnify runoff, erosion, and sediment transport processes into much more visible and destructive forces during flood events. The results of these processes have led to the formation of surface features with names such as playas, fans, bajadas, badlands, etc.; all of which are names that would undoubtedly be foreign to the citizenry of the midwestern or eastern United States.

The rainfall/runoff response associated with these landforms produces flooding and erosion problems that are dramatically different from the more familiar and classic riverine environment of the midwest or eastern United States. With the recent population increases sustained by "sunbelt states", such as Arizona and California, both residential and commercial development have begun to encroach into the normally dry floodplains of the desert washes and rivers, as well as onto the bajadas, alluvial fans, and pediments of the desert landscape.

The alluvial fans in these desert areas are especially prone to development pressures because of the elevated panoramic views that such locations provide to the prospective homeowner. However, if proper planning and engineering does not accompany such development, the unknowing homeowner may suddenly find his residence in the midst of a violent and destructive flood.

This has been previously demonstrated on poorly planned developments on alluvial fans in California. The communities of Rancho Mirage and Palm Desert, California incurred over $32,000,000 in flood damage as a result of severe storms in 1976 and 1979 (Anderson-Nichols 1981).

The dangers of alluvial fan development were even observed over 50 years ago. The community of Montrose, California (a suburb of Los Angeles) experienced a severe alluvial fan flood in 1934. This event resulted in the death of 39 people and reports of 45 others missing. Property damage was listed as 198 homes completely destroyed and 401 rendered totally uninhabitable. (Corps of Engineers, undated).

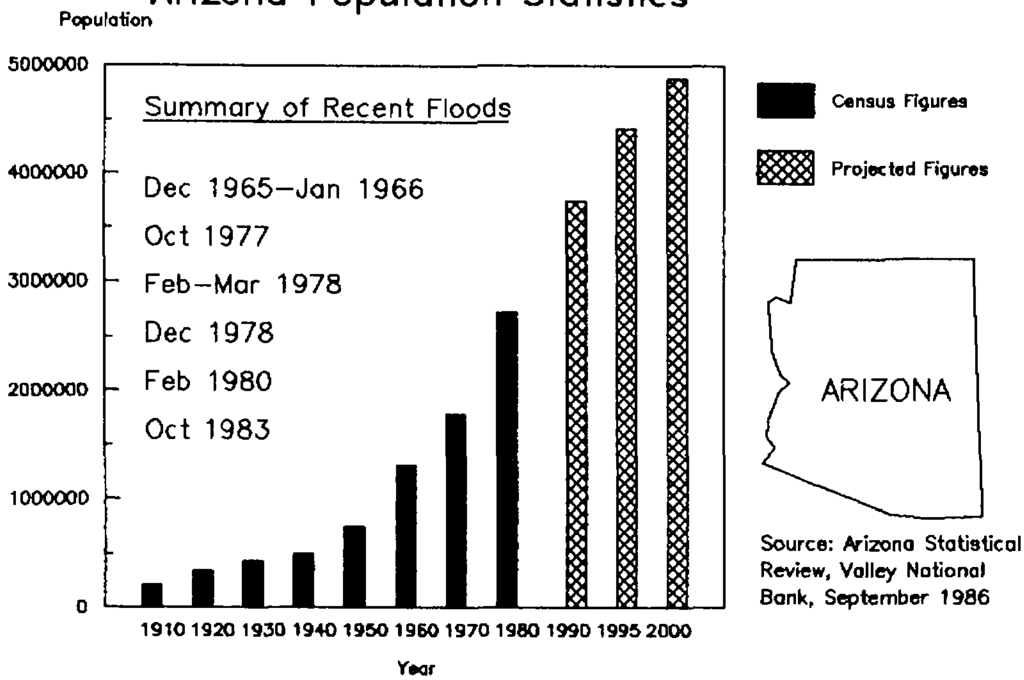
For the most part, it can probably be said that urbanization of desert floodplains and alluvial fans has taken place with little or no regard for the flooding and erosion hazards that would imminently occur. In those cases where some degree of hazard was acknowledged, it was probably either underestimated or analyzed with engineering techniques that were inappropriate for the site being developed. The engineering infrastructure (roads, bridges, utilities, etc.) that accompanied this urbanization frequently suffered from similar problems, i.e., engineering design was being prepared without a complete understanding of the severity and fluvial characteristics of the flooding and erosion hazards that are produced by desert landforms.

In Arizona's case, it is not difficult to understand the circumstances that led to this problem. Consider the following scenario:

1. In 1950, Arizona's total population was 749,587. Due to this small population base and the relative remoteness of many communities, the flood damage that did occur, and had historically occurred, probably received little publicity, especially outside of Arizona, where future Arizona residents were then located. Accordingly, the absence of frequent and widespread flood damage did little to focus efforts toward the development of effective floodplain management techniques for the desert environment.

2. By 1980, population figures had almost quadrupled to 2,718,425. Figure 1.1 indicates a significant upward population trend starting around 1960.

Figure 1.1
Arizona Population Statistics



3. During this period of population growth there were no effective local, state, or federal floodplain management programs in place to delineate flood hazards and to regulate development in flood prone areas.

4. The ephemeral washes and alluvial fans that are characteristic of desert environments are normally dry, only flowing during those occasions when rainfall exceeds losses due to interception, infiltration, and depression storage. The absence of frequent flooding, or flowing water, creates a false sense of security to the newcomer on the desert scene.

As a result of these factors, urbanization of desert floodplains was allowed to continue for many years before a series of severe floods occurred to focus attention on the problem. Substantial property damages were incurred in response to riverine floods of December 1965-January 1966, October 1977, February-March 1978, December 1978, February 1980, and October 1983. Many of these floods resulted in Federal Disaster Declarations.

Fortunately, during this same period, accelerated efforts were being made at federal, state, and local levels to cope with flooding problems on both a nationwide and local basis. This was evidenced by passage of the Flood Control Act of 1960, the National Flood Insurance Act of 1968 and, within Arizona, creation of the Flood Control District of Maricopa County in 1959 and passage of state legislation in 1978 mandating the establishment of county flood control districts in every county in Arizona. This legislation simultaneously authorized State financial and technical assistance to these county flood control districts.

These new programs promoted a definite awareness of the flooding problems that were being created by the desert population explosion in the west. Perhaps the most visible and publicized products of these programs were the federal Flood Insurance Studies and accompanying floodplain maps. Although these maps were a welcome improvement over the lack of floodplain information previously available, the maps were sometimes prepared using methodologies that did not totally acknowledge the very dynamic nature of the desert fluvial system, especially the alluvial fan. Such a problem is predictable in light of the fact that dense urbanization of such environments was a relatively new phenomenon that had not previously received widespread study by the engineering profession. As a result, there were no proven technical procedures available that could be applied with a reasonable degree of certainty that the characteristics of the system were being accurately simulated. In many cases there was probably a less than complete understanding of how the system would respond under actual flood conditions.

Although there may have been previous research completed on the behavior of desert fluvial systems, it is the opinion of the author that the majority of the practicing engineering community was probably not aware of much of this research because it previously had little to no practical application to the more conventional urban settings that engineers were used to dealing with in humid climates. However, with the increase in desert population, the engineer was now dealing with a new and unfamiliar environment that had been rarely observed during an actual flood event.

For several years now, the technical deficiencies of certain methodologies, when applied to desert fluvial systems, have been recognized. Accordingly, the engineering profession has become more aware of these problems and improved methods are being sought to provide more realistic floodplain analyses of the desert environment.

A primary purpose of this report is to examine flooding problems on alluvial fans in Arizona. This examination will focus on a review of existing floodplain management policies and an overview of specific analytical techniques that have, or might be, employed to quantify alluvial fan hazards. Application of National Flood Insurance Program (NFIP) criteria to highway planning and urbanization on alluvial fans will also be discussed. An overview will be presented relative to current policy utilized by the Arizona Department of Transportation (ADOT) in planning highway projects to comply with NFIP criteria.

A secondary objective of this study will be a review of the Corps of Engineers Regulatory Program (Section 404 of the *Clean Water Act*), as it is presently being applied to alluvial fan areas and ephemeral washes in Arizona. Discussions will focus on the impact of the "404" program on highway development in Arizona and explore clarification of such key terms as "ordinary high water mark" and "headwaters". ADOT's policy for compliance with "404" program criteria will also be evaluated

A concluding objective of this study will be to present an assessment of current technology being used to evaluate alluvial fan flooding and to outline any research that could be pursued to improve our ability to effectively manage the development of alluvial fans.

2 DESERT GEOMORPHOLOGY

Prior to discussing floodplain management policies and analytical techniques for alluvial fans, it is necessary to present a discussion of desert geomorphology in order that the reader may have a basic understanding of the processes that are responsible for fan development, as well as the characteristics of fans that create flooding and erosion/deposition hazards.

This section of the report is not meant to be an exhaustive discussion of alluvial fan systems. The available literature includes many excellent articles that are available to those readers who wish to pursue a more detailed review of alluvial fan formation, geology, and flooding characteristics. Many of these articles will be referenced herein since they have provided an invaluable source of information for this report.

2.1 The Desert Profile

Perhaps the most fundamental way to initiate a discussion on alluvial fans is to define a basic desert profile within which an alluvial fan is likely to occur. Cooke and Warren (1973) state that the simplest and most frequently recurring desert profile is composed of a mountain flanked by plains. Figure 2.1 illustrates this basic desert profile.

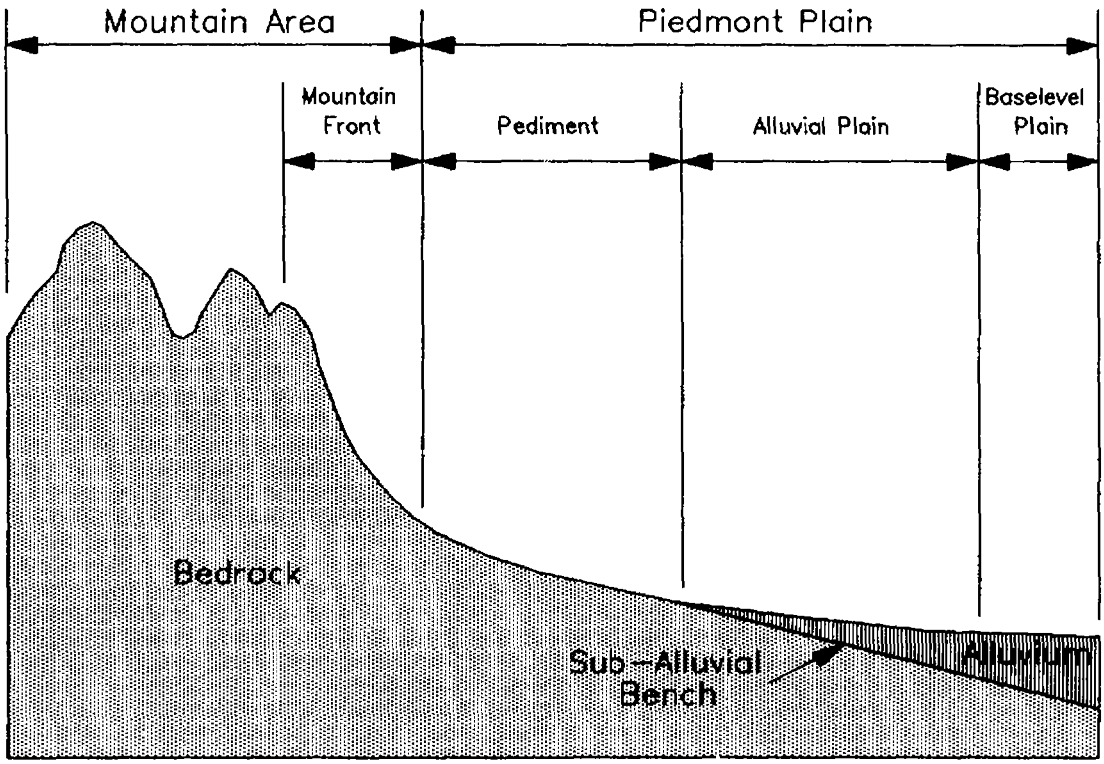
The piedmont plain, which extends outward from the mountain front, may contain two basic landforms: 1) pediments; and 2) alluvial plains. Alluvial plains may in turn contain playas (the lowest level of a closed desert drainage system), alluvial fans, and bajadas (an area of coalescing alluvial fans).

Although the focus of this report is on alluvial fans, certain similarities between fans and pediments can often lead to confusion when trying to identify these landforms. Accordingly, since pediments are a very common feature in Arizona, Section 2.3 is devoted to a brief discussion of pediment characteristics.

The remaining subsections of this chapter define an alluvial fan, present terminology used to describe the features of a fan, and identify the physical processes that are responsible for the formation and evolution of this unique landform.

Figure 2.1

Basic Desert Profile



2.2 The Alluvial Fan

An appropriate way to begin a discussion on alluvial fans would be to summarize some of the "fan" definitions that are found in the available literature. Such a list of definitions provides a view of alluvial fans through the eyes of several different researchers.

alluvial fans

1. Cooke and Warren (1973) - "Alluvial fans are deposits with surfaces that are segments of cones radiating downslope from points which are usually where streams leave mountains, but which may be some distance within the mountain valleys, or may lie within the piedmont plain."

2. Bull (1977) - "An alluvial fan is a deposit whose surface forms a segment of a cone that radiates downslope from the point where the stream leaves the source area. The coalescing of many fans forms a depositional piedmont that commonly is called a bajada."

3. Blissenbach (1954) - "An alluvial fan is a body of detrital sediments built up by a mountain stream at the base of a mountain front."

4. Doehring (1970) - "An alluvial fan is a relatively thick deposit of coarse, poorly sorted, unconsolidated clastics found as a semi-conical mass whose apex is adjacent to a mountain front. It has a relatively smooth subaerial surface which is inclined away from the mountain front."

Although this report focuses on alluvial fan activity in Arizona, it should be noted that the existence of alluvial fans is not limited to desert regions. Rachocki (1981) states:

> "Alluvial fans are found in valleys or in the foot-hills of mountains in all latitudes irrespective of climatic conditions. They were formed, and are still being formed, at the fronts of ice-caps and glaciers, as well as in moderate semi-arid and arid regions."

Cooke and Warren (1973) support this position by stating:

> "Alluvial fans are by no means confined to hot deserts. They occur in cold arid areas such as northern Canada (Leggett, Brown and Johnston, 1966) and also occasionally in humid areas. But in humid areas of perennial drainage, streamflow tends to remove the potential fan debris through the drainage system."

Fans do, however, appear to be more common in basin-range deserts. As reported by Rachocki (1981), Langbein and Schumm (1958) consider an annual rainfall rate of 10 to 14 inches to be an optimum range for the development of alluvial fans. Such a low rainfall rate creates a sparse cover of vegetation (thus exposing more surface area to erosion), yet still supplies sufficient water for transporting the eroded material. As is the case in Arizona, such rainfall most frequently takes the form of short-duration, high-intensity storms which produce substantial runoff rates that are capable of transporting large volumes of sediment and debris.

Until approximately the 1960 era, alluvial fan research has reportedly been very minimal in relation to other landforms. Rochocki (1981) indicates that approximately 100 research papers have been dedicated to alluvial fan processes during the past century. However, Bull (1977) considers these landforms as being the object of intensive study, especially during the last two decades.

The results of the author's literature search would indicate that there has been an increase in publications on alluvial fans during the past 20 to 30 years. Some of this increased attention is undoubtedly attributable to the urbanization of fans that began to occur during this period.

2.2.1 Alluvial Fan Terminology

Prior to discussing alluvial fan characteristics, it would be beneficial to define certain terms which are frequently used when analyzing fan processes. An excellent summary of alluvial fan terminology is presented by Rochocki (1981). For the reader's convenience, these definitions are repeated herein. In several cases, the definitions are cross-referenced to an originator. Not all of these terms will be used in the abbreviated discussion presented in this report.

abandoned channels	channels no longer connected to mountains (Denny, 1967)
abnormal fanhead incision	an incision of the fanhead caused by climatic changes or tectonic movement (Hooke, 1967)
alluvial fan	see Section 2.1
apex	the highest point of an alluvial fan, generally where the stream emerges from the mountains (Drew, 1873)
base	the term applied to the outermost or lowest zone of the fan (Blissenbach, 1954)
braid bars	flat gravel and sand bars separating several braided channels (Denny, 1965)
braided distributary channels	secondary channels that extend downslope from the end of the main stream or fanhead trench and are characterized by repeated division and rejoining (Bull, 1964)

cross-fan profile	a topographical profile of an alluvial fan, roughly parallel to the mountain front (Bull, 1964)
drainage basin	the area above the fan apex that is drained by the mountain stream (Bull, 1964)
ephemeral stream	a stream, or part of a stream, that flows in direct response to precipitation (Bull, 1964)
fan bay	the uppermost part of a fan that reaches into the mountain canyon (the term used by Davis, 1938; defined by Blissenbach, 1954)
fan-bench	small scale form of coalescing alluvial fan (the term used by Carter, 1975)
fan dissection	a general term to include both entrenchment and incision (Wasson, 1977)
fan entrenchment	downcutting into the fan surface of a channel that is contributing sediment to the fan surface. Entrenchment usually occurs during fan construction (Wasson, 1977)
fanhead	the area of the fan close to the apex (Blissenbach,1954)
fanhead trench	a stream channel entrenched into the upper, and possibly the middle, parts of a fan (Bull, 1964)
fan incision	downcutting into the fan surface by a channel that crosses the fan margin. Incision is usually associated with fan destruction (Wasson, 1977)
fan mesa	an alluvial fan remnant left standing in the process of fan degradation (the term used by Eckis, 1928; defined by Blissenbach, 1954)
fan segment	part of an alluvial fan that is bounded by changes in slope (Bull, 1964)

hanging fan	a fan formed by the in-filling of a small tributary valley whose surface is continuous with the older, dissected main surface (Lustig, 1965)
intermittent stream	a stream, or part of a stream, that flows only occasionally upon receiving water from seasonal sources such as springs, and from bank storage, as well as from precipitation (Bull, 1964)
intersection point	the point at which the main channel merges with the fan surface (Hooke, 1967)
midfan	the area between the fanhead and the outer fan margin (Blissenbach, 1954)
normal fanhead trenching	the incision produced by changes in slope in the upper reaches of the fan (Hooke, 1967)
paraglacial alluvial fans	fans which are products of an environment in the process of transition from predominantly glacial to predominantly fluvial conditions (Ryder, 1971)
piedmont plain	a broad sloping plain formed by the coalescence of many alluvial fans (Bull, 1964) synonyms: piedmont alluvial plain, compound alluvial fan, bajada.
pseudotelescopic structure	the structure of an alluvial fan created by the slumping of unconsolidated fan deposits (Blissenbach, 1954)
radial line	a straight line on the fan's surface extending from the fan apex to the fan toe (Bull, 1954)
rock fan	an area of bare or thinly covered bedrock at the point where the ravine slope is suddenly reduced (Wyckoff, 1966)
sand-finger fan	a small form of alluvial fan developed by the flow of water-saturated sands (the term used by Carter, 1975)

secondary alluvial fan	the alluvial fan at the base of the large primary alluvial fan, which consists mainly of re-worked primary fan deposits (Blissenbach, 1954)
sieve lobes	lobate masses of coarse and permeable deposits (Hooke, 1967)
subsidence cracks	cracks that develop between an area of near-surface subsidence and an area that remains stable (Bull, 1964)
superimposed fan	a fan developed during a secondary stage of deposition. Its growth is normally initiated by tectonic movements within the mountains that increase slope angles (Blissenbach, 1954)
telescopic structure of an alluvial fan	the structure of an alluvial fan formed by the repeated dissection and in-filling of the primary fan surface (the term applied by Blissenbach, 1945)
wadi fan	an alluvial fan at the mouth of a wadi; deposited during Pleistocene pluvial periods (Glennie, 1970)
wash	the action of vigorous branches of the stream cutting deep channels into the fan (Wyckoff, 1966)
wet-fan	the term used by Schumm (1977) to describe large alluvial fans created by streams in mountain foreland areas, and not in semiarid regions

2.2.2 Alluvial Fan Morphology

As can be inferred from the previous sections of this report, a mountain/plain interface could be considered a primary prerequisite for the creation of an alluvial fan (see Figure 2.1). A drainage channel, connecting the two areas, then becomes the conduit for transporting water, sediment, and debris from the mountain to the piedmont plain.

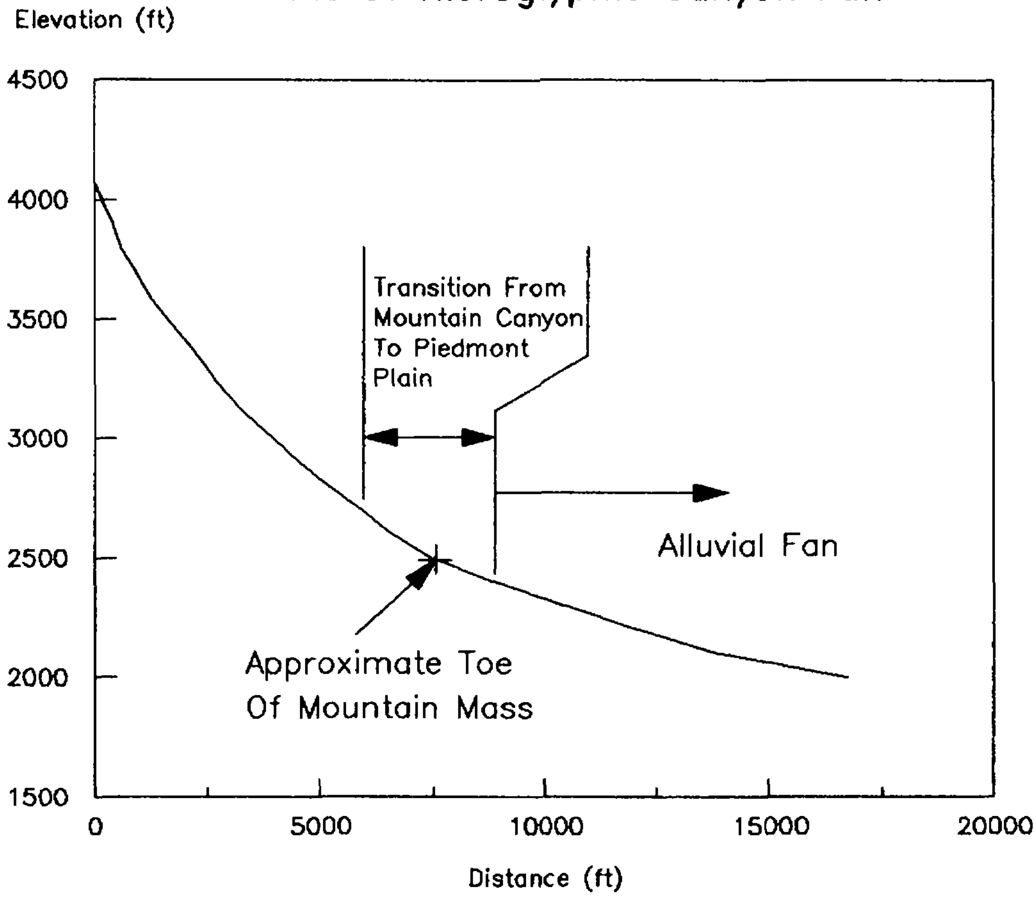
The connecting channel is confined to a relatively narrow width while traversing the mountain area. Narrow channel widths promote highly concentrated flow (large unit discharge), which in turn creates large sediment transport rates capable of moving sizeable volumes of sediment. Upon passing the interface between the mountain mass and piedmont plain, the channel is no longer confined by canyon walls. Accordingly, the flow is free to spread laterally, which causes a large decrease in unit discharge and a corresponding decrease in sediment transport rate. Being no longer able to transport the sediment/debris load delivered to the terminus of the confined channel, sediment deposition occurs on the piedmont plain and the birth/growth of an alluvial fan results. The shape of such fans are characterized by their resemblance to the segment of a cone.

As a point of interest, it should be noted that early theories on the mode of sediment deposition attributed this phenomenon to an abrupt change of channel slope as the water passed the mountain/piedmont plain interface. Bull (1977) attributes this theory to Chamberlain and Salisbury (1909) and indicates that it has, unjustifiably, continued to be published is some literature sources "despite contradictory arguments and evidence published by Bull (1964a), Melton (1965), Denny (1965), and Hooke (1972)." Bull notes that the slopes on the upper reaches of most fans are very similar to the channel gradients extending upstream from the fan apex. There is a decrease in slope in the downstream direction (all fans have concave radial profiles) but there is no abrupt slope change at the mountain/piedmont plain interface. Bull is a strong advocate of the "loss of channel confinement" theory as the most probable mechanism triggering the sediment deposition that creates the surface of an alluvial fan.

To illustrate the concavity of a stream profile on an alluvial fan, the author plotted a profile for Hieroglyphic Canyon, which has transported material onto an alluvial fan along the southwest side of the Superstition

Mountains near Apache Junction, Arizona. The results of this investigation, presented in Figure 2.2, indicate the existence of a very smooth, concave profile extending from the mountain onto the alluvial fan.

Figure 2.2
Profile of Hieroglyphic Canyon Fan



Clearly, there is a substantial reduction in slope from the upper end of the watershed to the toe of the fan. However, this decrease in slope is gradual, and, even though it will create a reduction in sediment transport capacity, the reduction due to a slope change will undoubtedly be substantially less than that resulting from an abrupt reduction in unit discharge as channel flow leaves the confines of a mountain canyon and spreads across a piedmont plain. The author agrees with Bull's hypothesis that a change in channel geometry is the primary mechanism for sediment deposition on a fan surface; however, the gradual slope reduction also has to be considered as a contributing cause for this deposition, although to a much lesser extent than the change in channel geometry.

The morphology of an alluvial fan is dependent upon a complex interaction of several variables. Bull (1968) lists such factors as: 1) area, lithology, mean slope, and vegetative cover of the source area; 2) slope of the stream channel; 3) discharge, climatic, and tectonic environment; and 4) geometry of the mountain front, adjacent fans and the basin of deposition. The role of each of these variables in fan formation is obvious when viewed within the context that a fan is formed by the erosion and transport of material from a mountain area onto an adjacent plain. All the listed variables in the first three categories are directly connected to the erosion or sediment transport process. The variables in category number four address physical constraints that place limitations on the available area of deposition. For example, the geometry of a mountain front might dictate how abruptly a channel might transition from the confined geometry of a canyon to the unconfined environment of the fan surface. The face of a mountain front might also include irregular outcrops of bedrock that would prevent the flow of water along an unobstructed 180 degree arc adjacent to the mountain front. Adjacent alluvial fans would obviously reduce the lateral area available for fan growth. The basin of deposition might terminate along a river. Base-level changes in the river could induce headcutting or aggradation on the fan surface.

Some attempts have been made to describe the morphology of alluvial fans with mathematical relationships. Bull (1962a) proposed the following relationship between fan area and source area:

$$A_f = cA_d^n \text{. . . . . (2.1)}$$

where A_f = fan area

A_d = drainage basin area

c = empirically derived coefficient

n = empirically derived exponent

Based on a sampling of seven fans (by various researchers), an average value for n was found to be 0.93. The values used to compute this average ranged from 0.8 to 1.01.

Unfortunately, the variation in the coefficient, c, is much larger. For the same seven fans, c was found to vary from 0.15 to 2.1. This wide variation is attributed to variables such as drainage basin lithology, climate, mean slope, and the amount of space available for fan deposition. Relative to basin lithology, Bull notes that fans derived from mudstone areas are approximately twice the size of their source areas, while fans derived from quartzite basins are only one-sixth the size of the source areas. Tectonic tilting has also been cited as a major factor in causing a wide variation in the coefficient of Equation 2.1.

Based on an investigation of fans in western Fresno County, California, Bull (1964) also developed empirical relationships between: 1) drainage basin area and fan slope; and 2) fan area and fan slope:

for drainage basins comprised of 48% to 86% mudstone & shale;

$$S_F = 0.23 A_D^{-0.16} \quad (2.2)$$

$$S_F = 0.034 A_F^{-0.28} \quad (2.3)$$

and for drainage basins comprised of 58% to 68% sandstone;

$$S_F = 0.022 A_D^{-0.32} \quad (2.4)$$

$$S_F = 0.025 A_F^{-0.34} \quad (2.5)$$

where S_F = overall fan slope (ft/ft)

A_D = drainage basin area (square miles)

A_F = fan area (square miles)

The reader should be cautioned that Equations 2.2 through 2.5 were developed from site-specific data. Accordingly, the coefficients and exponents contained in those equations would not necessarily be appropriate for application to other sites.

Troeh (1965) presents the theoretical development of a three-dimensional equation to describe the surface of an alluvial fan. Based on the equation of a right circular cone, and adding a component to reflect the concavity of the radial fan slope, the following relationship was derived:

$$Z = P + SR + LR^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.6)$$

where Z = elevation at any point on the surface of the cone (fan)

P = elevation at the central point of the cone (theoretical fan apex)

S = slope of the fan at point P

R = the radial distance from point P to point Z

L = half the rate of change of slope along a radial line

The location of point P in Equation 2.6 is found by the projection of a perpendicular from the tangents to several contour lines on the fan. The point which most nearly fits the intersection of all the perpendiculars is considered as point P.

For a given fan, Equation 2.6 is ultimately reduced to a function of R. Troeh demonstrates the solution of the equation by writing Equation 2.6 for three different points on a fan surface, and then performing a simultaneous solution of three equations containing three unknowns (P, S, and L). Application of this procedure (by Troeh) to a pediment near Gila Butte, Arizona produced excellent agreement with actual landform contours.

2.2.3 Mechanisms of Alluvial Fan Deposition

A review of alluvial fan literature indicates that fans are formed in response to *water-laid deposits* and *debris deposits*. A third mechanism, called a *sieve deposit*, has also been observed on alluvial fans. Each of these phenomena are discussed in the following paragraphs.

1) *water-laid deposits*

Bull (1977) describes water-laid deposits as "sheets of sediments" that are deposited as surges of sediment-laden water are dispersed across the fan surface after leaving the confines of a well-defined channel. The sediment/water mixture is transported across the fan by a dense pattern of shallow, braided, distributary channels that generally have a depth of flow ranging from about 4" to 20". As is characteristic of braided systems, these shallow channels are prone to rapid sedimentation which causes a diversion of water to a new flow path or braid.

Rachocki (1981) presents excellent photographic documentation of both pure sheetflow and shallow braided flow that were observed on man-made alluvial fans created as part of a gravel pit operation. Rachocki's photographs illustrate surges of pure sheetflow, occurring near the apex of the fan, which transition into a classic braided-flow pattern as water moves further down the fan surface.

A second type of water-laid deposit described by Bull refers to the filling of channels that have been temporarily entrenched into the fan surface. Although he does not elaborate on this phenomenon, it is assumed that he is referring to larger and more well-defined channels than those associated with the braided distributary system. These larger channels are also subject to receiving overloads of sediment which can cause aggradation and subsequent backfilling. Bull notes that the sediment deposits in these larger channels are coarser-grained and more poorly sorted than those deposited in the shallow, braided distributary channels. The thickness of these deposits is most frequently found to be between 2" and about 40".

2) *debris-flow deposits*

The second major type of fan deposition occurs in response to debris flows, which are very viscous, dense mixtures of water and sediment. Hooke (1967) describes debris flows as quasi-plastic substances which leave deposits consisting of cobbles and boulders imbedded in a matrix of fine material. Due to the very high viscosity in debris flows, the settling velocity of individual sediment particles is greatly reduced, thus allowing debris flows to retain relatively large particles in suspension.

Debris flows can be identified in the field as longitudinal lobes or tongues. In the author's opinion they have a strong resemblance to fresh lava flows.

Sharp (1942), as referenced by Hooke (1967), also describes the probable formation of bouldery, sharp-crested levees on some alluvial fans as being created in response to coarse material being accumulated in front of a debris flow and subsequently being shoved aside by the advancing debris front. Levees formed in this manner tend to confine the remainder of the debris flow. Hooke also notes that some debris flows may overflow the banks of an entrenched channel and create levees along the channel banks.

A second category of debris flows has been described by Bull (1977) as a "mudflow". As the name might imply, a mudflow is "a type of debris flow that consists mainly of sand-size and finer material." As a matter of interest, Bull notes that the term "mudflow" is often used in a generic sense to refer to all types of debris flows, since mud is a common ingredient in all such flows.

3) *sieve deposits*

Unless the alluvial fan surface is formed with high concentrations of silts and clays, it will tend to be relatively permeable. Under such conditions, water flowing over the fan surface will be subject to large infiltration losses. When the infiltration rates are high enough, the entire flow may infiltrate into the fan surface prior to reaching the toe of the fan. When this occurs, the sediment being carried by the water will be deposited at the point where there is no longer sufficient water to transport the material. This phenomenon was described and named by Hooke (1967):

> "Because water passes through rather than over such deposits, they act as strainers or sieves by permitting water to pass while holding back the coarse material in transport. I call the lobate masses thus formed "sieve lobes" or "sieve deposits" and the mode of formation is sieve deposition."

Hooke gives a very detailed account of the formation of sieve deposits on laboratory fans. He also made a field identification of such deposits on several fans in California, and points out that sieve deposits may be initiated by the complete infiltration of the transporting water or by a break in fan slope.

2.2.4 Alluvial Fan Dissection

Depending upon the interaction of the many variables that influence alluvial fan morphology, the fan surface may exhibit varying degrees of channel incisement or dissection. Such incisement might take the form of a major fanhead trench, that could extend from the apex to midfan, or it might be localized incisement resulting from rain falling directly on the fan surface. The types of, and possible reasons for, fan dissection are discussed in the following paragraphs.

1) ***fanhead trench***

A fanhead trench is connected directly to the trunk stream feeding the apex of a fan. The depth and length of these trenches may vary from fan to fan. Several hypotheses have been presented to explain their occurrence. These include: 1) climatic changes which might cause a substantial disruption in the amount of sediment being delivered from the mountain area to the fan; 2) tectonic changes which can cause differential movement along the mountain/alluvial fan interface (such movement might occur as the result of normal mountain building processes or movement along a faultline); and 3) the occurrence of exceptionally large floods (Denny 1967) which may create sediment transport rates far in excess of the available sediment supply.

Bull (1977) presents a mathematical expression relating tectonic activity to both the entrenchment and aggradation of alluvial fans. For fan deposition to occur along the mountain front, the following inequality must be maintained:

$$\frac{\Delta u}{\Delta t} \geq \frac{\Delta w}{\Delta t} + \frac{\Delta s}{\Delta t} \quad \text{(2.7)}$$

where $\Delta u/\Delta t$ = the rate of change of tectonic uplift for the mountain

$\Delta w/\Delta t$ = the rate of change of channel downcutting in the mountain

$\Delta s/\Delta t$ = the rate of change of fan deposition at the mountain front

Conversely, when uplift becomes less than channel downcutting in the mountain area, channel entrenchment will tend to extend onto the fan surface and move the loci of deposition downslope from the fan apex. Under such conditions, the fan head is bypassed as an area of deposition and will become prone to localized erosional processes. Bull defines this condition with the following inequality.

$$\frac{\Delta u}{\Delta t} < \frac{\Delta w}{\Delta t} > \frac{\Delta e}{\Delta t} \quad \text{(2.8)}$$

where $\Delta u/\Delta t$,
and $\Delta w/\Delta t$
are as defined for Equation (2.7) and
$\Delta e/\Delta t$ is the rate of erosion of the fan deposits adjacent to the mountain.

Denny (1967) presents a hypothetical case where local gullying on the abandoned upper segments (that have been bypassed by a fanhead trench) of the fan may cut deeper into the fan surface than the adjacent fanhead trench. This creates a condition where bank erosion of the fanhead trench may cut through to a local gully and allow the gully to capture the flow of the fanhead trench. This phenomenon, which is called channel "piracy", will shift the loci of deposition to a new point on the fan. Channel piracy is an important mechanism in the development of an alluvial fan.

Channel entrenchment can provide both lateral movement of sediment deposition across the width of fan as well as lengthwise along a radial line extending from the fan apex to the toe. Lateral movement can be caused by channel piracy or through channel avulsions that might be created by plugs of mudflow or debris flow. Such lateral shifting might also occur as a simple function of one part of the fan being raised sufficiently higher than an adjacent part, thus creating the potential for a steeper gradient of flow towards the lower area.

Deposition along a radial line can occur in response to an imbalance between sediment transport rate and supply. This phenomenon can move the location of the intersection point (point at which the invert of the entrenched channel intersects or merges with the fan surface) up and down a radial line, thus allowing sediment to be deposited either closer to, or farther from, the fan apex. For example, an excess of sediment (beyond the existing transport capacity) would cause deposition in the channel and a subsequent retreat of the intersection point towards the fan apex. Conversely, should existing transport capacity exceed the sediment supply, the channel bed would tend to degrade and advance the intersection point towards the fan toe.

Based on observations of laboratory fans, Hooke (1967) relates the following description relative to the movement of the intersection point:

> "The intersection point on laboratory fans is commonly near midfan. This appears to be because fluvial deposition predominates near the toe and occurs without downfan migration of the intersection point, while overbank debris flow deposition predominates near the fanhead. Thus the average radial position of the intersection point should be related to the relative importance of debris flows and fluvial processes in transporting material to a fan.
>
> The intersection point on laboratory fans shifted gradually due to debris-flow and fluvial deposition. The intersection point would migrate up-fan as low banks of the main channel were buried. Subsequent water flows then eroded a new channel offset laterally from the previous course."

Bull (1977) provides the following account of radial deposition:

> "Migration of the depositional area along a given radial line occurs as a result of entrenchment or backfilling of the stream-channel extending from the source area. Fanhead trenches commonly extend half the length of the fan. Some streams are permanently entrenched, and may have channel bottoms that are as much as 50 meters below a fan surface with an old soil profile. Other fanhead trenches appear to be temporary, being less than 15 meters below a fan surface having no visible soil profile; and having been entrenched and backfilled one or more times before the present channel downcutting."

2) *dissection not related to fanhead trenching*

Channels or gullies on a fan can also occur without being connected to a fanhead trench. As mentioned in the previous paragraphs, fanhead trenching can cause sediment deposition to bypass the fanhead area near the apex.

Being deprived a supply of new sediment from the mountain area, these bypassed fanhead areas will begin to erode and create a local drainage network to dispose of precipitation falling directly on the fan surface.

A change in base level along the toe of a fan can also initiate dissection of a fan surface or accelerate (deepen) existing dissection. A common example of this type of base level change occurs when a stream is flowing along the toe of a fan. The location of such a stream can cause fan dissection in two ways. The first way would accompany a long-term lowering of the base-flow in the stream or an actual lowering of the streambed. Such a condition would create a steep slope from the fan toe to the streambed. Water flowing over such a precipice would cause headcutting back into the fan surface.

The second method would accompany a swing in the stream-flow alignment either into or away from the toe of the fan. As the stream swings into the fan, the toe would be undercut, causing a sharp drop-off (as described previously) from the fan surface to the streambed. Conversely, as the stream alignment migrates away from the fan toe, an aggradational tendency will be induced (Blissenbach 1954).

Bull (1964) presents an interesting statistic on the location of fanhead channels relative to a *medial position*, which is defined as a radial line projected perpendicular to the apex at the mountain front. This definition assumes that water has the freedom to flow through a 180 degree arc upon passing the mountain front. Based on a sample of 75 fans in California, two thirds of the fanhead channels were found to be located within 30 degrees of the medial line. Only three channels were found to have a deviation of more than 60 degrees from the medial position. Bull concludes that the large concentration of channels within a 30 degree arc on either side of the medial line implies that this central segment of the fan is prone to receiving more deposition than those areas nearer the lateral edges of the fan. This is consistent with the general shape of a fan, which is a cone-shaped landform with a convex cross-profile. Such a profile has a maximum depth at the center of the cone.

2.3 Pediments

Although this report is directed towards a discussion of engineering problems associated with the development of alluvial fans, an encounter with a pediment may be a more common occurrence for development in Arizona. Accordingly, a very brief discussion of pediment characteristics is provided to alert the reader to the existence of these two different landforms.

A review of current literature reveals considerable differences of opinion on the formation of pediments, and even the definition of a pediment. Several definitions obtained from available literature are summarized as follows:

pediments

1. Cooke and Warren (1973, page 196) - "In most cases, the pediment is a complex surface, comprising patches of bedrock and alluvium, in places capped by weathering and soil profiles, punctuated by inselbergs, and scored by a network of drainage channels."

2. Bull (1977) - "In trying to distinguish an alluvial fan from a pediment in the field, it is useful to remember that alluvial fans are formed in a depositional environment and that pediments are formed in an erosional environment. Many pedimented areas have a large number of streams and rills that drain to the piedmont, but an alluvial-fan piedmont has fewer streams each acting as a major conduit for water and sediment that is transported to the fanhead. Bedrock knobs rarely protrude through the alluvium of fans but are typical of pedimented terrains, where a veneer of alluvium and colluvium mantles bevelled bedrock. .... As a general guideline, fans may be distinguished from pediments as being landforms where the thickness of deposits is more than 1/100 the length of the landform."

Bull goes on to state that the continued lack of tectonic uplift (along the mountain front) will change the depositional environment of an alluvial fan to an erosional environment where pedimentation is the main process operating on the landscape (see Equations 2.7 and 2.8). He attributes the scarcity of earthquakes in south-central Arizona as a prominent factor for the abundance of pedimented landscapes which are typical of this area.

3. Doehring (1970) - "The term pediment, as used herein, refers to a low gradient, subplanor, topographic surface located at the foot of a mountain mass in an arid or semiarid, mid- to low-latitude desert region and which meets the mountain front at an angular junction. Pediments are underlain by consolidated rock, do not follow lithologic or structural anisotropies or inhomogeneities, are usually fan-shaped in plan, and may have an alluvial veneer not exceeding 50 ft. in thickness."

4. Hadley (1967) - "Pediments are erosional surfaces of low relief, partly covered by a veneer of alluvium, that slope away from the base of mountain masses or escarpments in arid and semiarid environments."

As with alluvial fans, pediments most frequently occur between a mountain front and an alluvial plain. However, unlike alluvial fans, pediments may not always be part of a clearly defined drainage system. The surface of a pediment often occurs in more than one drainage system and it may be impossible to assume that present drainage networks on a pediment were associated with its formation (Cooke and Warren, 1973).

Due to similarities in their locations along a mountain front, and in some cases their similarity in shape to a segment of a cone (Hadley 1967, presents a topographic map of a pediment which has a very distinct fan shape), it can be difficult to differentiate between a pediment and a fan without extensive field investigations. Hadley notes that most pediments exhibit an irregular plan view, with the irregularities more pronounced where the pediment intersects rock surfaces with varying resistance to erosion. Some researchers (Gilluly, Johnson, and Rich) also present field data that describe pediments as widening from a canyon mouth to the downstream end.

From a distance, pediments have been described as having a relatively smooth surface. However, close examination of the surface will usually reveal an intricate pattern of dissection. Gilluly (1937) (as referenced by Hadley, 1967) describes a pediment on the Ajo quadrangle of Arizona as having dissected drainage channels approximately 40 feet deep near the head of the pediment. The channels were noted to decrease in depth in the downstream direction.

Based on an analysis of topographic maps, Doehring (1970) reports that: "the drainage texture (spacing of low order drainage channels) tends to become finer in a headward direction on pediments but remains relatively constant on alluvial fans." Doehring's paper presents a methodology, called the "texture curve method" to identify the drainage texture of landforms from topographic maps.

Relative to surface deposits, Hadley (1967) indicates that pediments have been described as having from no alluvial cover to over 100 feet of gravel and fine-grained alluvium veneer. Causes for this variation in thickness are attributed to base-level changes, stream discharge from the mountains, and climatic changes. Hadley also references an interesting suggestion by Tator (1952) that the thickness of pediment alluvium often averages about the depth of effective stream scour.

Although there is no consensus of opinion regarding the process of pediment formation, Hadley (1967) notes that two processes are generally recognized as the most probable cause of pedimentation: 1) lateral planation by streams; and 2) weathering and removal of debris by rill wash and unconcentrated flow.

The theory of pediment formation by planation (reduction of a land area by erosion to a nearly fat surface, Webster's New World Dictionary, 1984) assumes that stream-flow emanating from the mountains will continually migrate back and forth across the pediment surface and gradually wear it down by erosion. Obviously, this theory apparently makes the assumption that sediment deposition is not a prominent process on a pediment surface. Hadley (1967) in referencing the planation theory to one of its strong proponents (Douglas Johnson) summarizes Johnson's comments:

> "...pediments, or rock planes, as he called them, are the product of normal stream erosion. Pediments ("rock planes") result from the fact that the heavily laden streams of arid regions are not able to cut vertically; they therefore tend to migrate laterally."

The second theory (weathering and rill wash) assumes that material will be weathered from the mountain front and removed by rill wash, unconcentrated flow, or stream action. As noted in the preceding paragraph, this theory must also assume that the weathered material will be transported across the pediment rather than being deposited upon it.

In comparing these two theories, many researchers feel that pediment formation may be a combination of both processes, although Hadley (1967) indicates that the theory of weathering and rill wash seems to be the more widely accepted of the two scenarios.

After reviewing several technical papers on alluvial fans and pediments, the author is left with the definite impression that a major difference between pediments and alluvial fans is that fans are a depositional landform while pediments are an erosional landform. It is interesting to note that Bull (1977) indicates that a continued lack of tectonic uplift may transform an alluvial fan into a pediment environment. This is in concert with the predictions of Equations 2.7 and 2.8, which relate the rates of change of tectonic uplift to channel downcutting, fan deposition, and fan erosion. In other words, a fan will tend to transition into a pediment environment when the erosional forces dominate over the depositional forces.

Due to the lack of depositional tendencies on a pediment, it would appear that they might be a more stable environment (from a drainage perspective) than a fan. In the absence of large debris flows, and general sediment deposition, pediments should not be prone to abrupt channel shifting during flood events. Although Denny (1967) indicates that channel piracy may still occur on pediments, he also states that many of the gullies on pediments are eroded into the rocks of the mountain block.

Relative to drainage issues, Cooke and Warren (1973) present an excellent summary of the topography of a pediment. Excerpts from their description are quoted as follows:

> "Although many published accounts may give a contrary impression, a pediment which is a clean, smooth bedrock surface is rare indeed. In most cases, the pediment is a complex surface, comprising patches of bedrock and alluvium, in places capped by weathering and soil profiles, punctuated by inselbergs, and scored by a network of drainage channels. ....
>
> Another important yet neglected feature is the presence of cut-and-fill features on pediments. Channels 1-3 meters deep and now filled with alluvium have been described....(by various researchers). The presence of buried channels indicates that the relations between erosion and sedimentation in the pediment zone have changed during the period of pediment development, probably as a consequence of changed environmental circumstances. The filling of channels and other depressions in bedrock by alluvium is commonly responsible for the general smoothness of many pediments.
>
> Closely related to buried channels are pediment drainage nets. These, too, have rarely been considered. There are three common types. (i)

Channels occurring in the upper part of the piedmont plain, which commonly form a distributary system and die out lower down the surface. Such channels often straddle the piedmont angle, [piedmont angle is the angle produced by the intersection of the lines representing the slope of the mountain front and the slope of the piedmont plain (Cooke & Warren, 1973)] and they are deepest at intermediate positions on their longitudinal profiles. (ii) Channels occurring on the lower part of the piedmont plain, which are generally deepest at the lowest point in their longitudinal profiles, and usually form part of a drainage system that has been rejuvenated on one or more occasions by lowering of base-level. Such systems may cover the whole pediment. When drainage in this type of net is rejuvenated it often leads to the destruction of the pediment surface. (iii) On relatively undissected surfaces, often between areas characterized by types (i) and (ii), drainage nets may consist of complex and frequently changing patterns of shallow rills.

These drainage nets are similar in pattern and location to those on alluvial fans, and they may perhaps be explained in similar terms. Type (i) is probably generated by drainage in the catchment area behind the pediment, type (ii) may result from runoff on the pediment surface itself, and type (iii) probably arises from rillflow, perhaps characteristic of declining sheetfloods, in the intermediate zone. Drainage incision may reflect adjustments to climatic or tectonic changes, or changes in the nature of waterflow within the system. Such changes could have accompanied pediment formation, or they could be younger and lead to pediment destruction".

3 NATIONAL FLOOD INSURANCE PROGRAM ACTIVITY IN ARIZONA

One of the principal objectives of this study is to examine the application of NFIP criteria to floodplain management, especially on alluvial fans, and to evaluate ADOT procedures for coordinating the planning and design of highway projects in floodplain environments with the Federal Emergency Management Agency (FEMA).

The following subsections of this report address these issues at the federal, state, local, and ADOT level.

3.1 Federal Program

As indicated previously, Congress passed the National Flood Insurance Act in 1968. This Act created the National Flood Insurance Program (NFIP) which was designed to reduce future flood losses through local floodplain management efforts and to transfer the costs of residual flood losses from the general taxpayer to the floodplain occupant.

An integral part of this program was the development of flood risk studies to provide data for local floodplain management and to establish actuarial insurance rates.

Based on an estimate of projected property-at-risk, FEMA routinely employs different levels of detail when preparing these risk studies (FIS/FEMA,1984). Three levels of study detail are defined as:

- detailed flood insurance study
- limited detail flood insurance study
- existing data study

The level of study detail in these three categories ranges from the preparation of very detailed Flood Insurance Rate Maps (FIRM) to simple approximations of floodplain limits based on existing technical data or historic floods.

Communities participating in the NFIP are required to use these studies and floodplain maps and to enact certain floodplain management measures (in accordance with the amount and nature of flood risk data provided by FEMA) to regulate new floodplain construction in order to reduce future flood damage.

The policies and management criteria embodied by the NFIP are listed in 44 CFR (Code of Federal Regulations), Parts 59 through 77, dated October 1, 1986 (see Federal Emergency Management Agency, 10/1/86). This document does not specifically make reference to alluvial fan flooding. However, several special flood, mudslide, and flood-related erosion hazard zones are defined. These zones are defined in Table 3.1

In order to provide technical guidelines for engineers who are retained to prepare Flood Insurance Studies (FIS) as part of the NFIP, FEMA has published a document entitled "Guidelines and Specifications for Study Contractors", September 1985. Appendix 5 of that document outlines a specific procedure for preparing Flood Insurance Studies on alluvial fans. It also states that Special Flood Hazard Areas on alluvial fans are to be identified as Zone AO, which is further defined as follows:

"Zone AO is the flood insurance rate zone that corresponds to the areas of 100-year shallow flooding (usually sheet flow on sloping terrain) where average depths are between 1 and 3 feet. Average whole-foot depths derived from the detailed hydraulic analyses are shown within this zone."

Accordingly, this review of federal flood control programs indicates that efforts have been made to address the unique flooding problems on alluvial fans. Discussions on details of the technical procedures will be presented in subsequent sections of this report.

Table 3.1

Definition of FEMA Flood Hazard Zones

Zone Designation	Definition
A	Area of special flood hazard without water surface elevations determined.
A1-30, AE	Area of special flood hazard with water surface elevations determined.
AO	Area of special flood hazards having shallow water depths and/or unpredictable flow paths between 1 and 3 feet.
A99	Areas of special flood hazard where enough progress has been made on a protective system, such as dikes, dams, and levees, to to consider it complete for insurance purposes.
AH	Areas of special flood hazards having shallow water depths and/or unpredictable flow paths between 1 and 3 feet, and with water surface elevations determined
V	Areas of special flood hazards without water surface elevations determined, and with velocity, that is inundated by tidal floods (coastal high hazard area).
V1-30, VE	Areas of special flood hazards with water surface elevations determined and with velocity, that is inundated by tidal floods (coastal high hazard area).
VO	Area of special flood hazards having shallow water depths and/or unpredictable flow paths between 1 and 3 feet and with velocity.
B, X	Area of moderate flood hazard.
C, X	Area of minimal hazards.
D	Area of undetermined, but possible, flood hazards.
M	Area of special mudslide (i.e., mudflow) hazards.
N	Area of moderate mudslide (i.e., mudflow) hazards.
P	Area of undetermined, but possible, mudslide hazards.
E	Area of special flood-related erosion hazards.

3.2 State Program

Floodplain management at the State level encompasses several areas of responsibility. By approval of Executive Order No. 77-6 on September 27, 1977, Governor Raul Castro directed each State agency to take the necessary action to support the goals of the NFIP. Brief discussions of the State's responsibility and programs are presented in the following subparagraphs.

3.2.1 State-Owned Lands

Under NFIP criteria, a State is considered a "community" and must comply with the minimum floodplain management criteria set forth in 44 CFR, Part 60, as a condition to the purchase of a Standard Flood Insurance Policy for a State-owned structure or its contents.

Discussions with the Arizona State Land Department (ASLD) reveals that State-owned lands located within delineated floodplains are carefully reviewed to insure that any proposed development on such lands is done in accordance with the criteria established by the NFIP. Representatives from ASLD indicate that they routinely send floodplain development plans to the Arizona Department of Water Resources (ADWR) for review, and also coordinate such plans with the floodplain managers of the local jurisdiction within which the property is located.

3.2.2 State Flood Control Assistance Programs

The Arizona State Legislature enacted several programs during the 1970's to promote the planning and installation of flood control projects. Since these programs do not specifically address alluvial fan problems, only a brief discussion will be presented for each program.

The Flood Control Assistance Program, which was created in 1973, authorized the State of Arizona to reimburse local sponsors for 50% of the cost of local expenditures for right-of-way, utility, and road relocation work required for federally approved flood control projects.

Two additional assistance programs were adopted by the State Legislature in 1978. These programs authorized county flood control districts to request the Arizona Department of Water Resources (ADWR) to conduct engineering studies and to develop plans to control specific flooding problems within the districts. To complement this planning program, the Legislature simultaneously enacted a financial assistance program which allows the State to fund 50% of the installation cost of any flood control plan found to be economically justified as a result a completed State sponsored planning study.

A fourth program, approved by the Legislature in 1979, authorized the State to provide low-interest loans to county flood control districts for up to 25% (not to exceed two and one-half million dollars) of the installation cost of a flood control project developed under the State flood control planning program.

3.2.3 State Coordinating Agency

The State program that is perhaps most closely associated with the implementation of the NFIP in Arizona is the State Coordinating Agency (SCA). FEMA encourages (44 CFR, paragraph 60.25) states to demonstrate a commitment to the minimum floodplain management criteria set forth in the NFIP by designating an agency of state government to be responsible for coordinating the Program aspects of floodplain management in the state.

At the present time, ADWR has been designated as Arizona's State Coordinating Agency. The NFIP lists 12 duties and responsibilities that the SCA should maintain a capability to perform (following duties are paraphrased per Bond, ADWR, 1982):

1. Enact enabling legislation in floodplain management.
2. Encourage and assist communities in qualifying for participation in the NFIP.
3. Assist communities in the adoption of ordinances.

4. Provide communities and the public with information on floodplain management.
5. Assist communities in disseminating elevation requirements for flood-prone areas.
6. Assist in the delineation of flood-prone areas.
7. Recommend priorities for Federal floodplain management activities within the State.
8. Notify the FIA (Federal Insurance Administrator) of community failures in floodplain management.
9. Establish State floodplain management standards.
10. Assure coordination and consistency of floodplain management activities with other agencies.
11. Assist in the identification and implementation of flood hazard mitigation recommendations.
12. Participate in floodplain management training activities.

Due to limited staff capability, ADWR has been unable to fulfill 100% of these obligations, but for the most part, ADWR has been very effective as the SCA in promoting the goals of the NFIP in Arizona.

To summarize this overview of state floodplain and flood control policies, it can be concluded that the State of Arizona has been very active in the last 15 years in developing programs to mitigate potential flood damage and to support the goals of the NFIP. However, none of the State programs have published official policies dealing specifically with alluvial fan flooding.

3.3 Local Programs

The NFIP provides local communities with a very comprehensive set of floodplain management criteria and a set of floodplain maps which delineate specific hazard areas. In Arizona, these criteria have presently (October 16, 1987) been implemented by 87 communities, cities, and counties.

The NFIP criteria is intended to be applied to all delineated flood prone areas, including alluvial fans. FEMA representatives in Region 9 were asked to provide a list of alluvial fans in Arizona for which floodplain delineations had been prepared. Access to such information would provide an excellent data base to locate communities that are attempting to regulate development on alluvial fans. Unfortunately, FEMA was unable to provide this information.

As a parallel effort to acquire input on how communities are attempting to use NFIP criteria to manage development on alluvial fans, a questionnaire was developed which presented specific questions on management policies, technical procedures, flood damages, and research needs for the alluvial fan environment. This questionnaire was sent to every county engineer/flood control district in Arizona, as well as to all major towns and cities that were thought to have possible contact with alluvial fan problems. Questionnaires were also distributed to ADOT, ADWR and several private consultants who were known to have had previous exposure to engineering problems on alluvial fans. A total of 49 copies of the questionnaire were circulated for input to this report. All local agencies that received the questionnaire had adopted floodplain regulations that met minimum NFIP criteria. Said agencies were also participating in the Regular Phase of the NFIP.

Unfortunately, the response to the questionnaire was very limited. Replies were only received from 16 local (non-state) agencies. It is the opinion of the author that this low response is due to the fact that the majority of the local agencies do not presently have development occurring on a true alluvial fan. As a result, they are not faced with the potential devastation that has historically been experienced on some of the classic alluvial fans in California (Palm Desert and Rancho Mirage). The author has been exclusively involved in flood control engineering in Arizona for the last 14 years. During that period he has not witnessed, or read reports of, flood damage on a classic, active alluvial fan that is similar to those referenced for California.

The absence of development on active alluvial fans in Arizona is supported by the responses on the questionnaires. With the exception of the Pima County Department of Transportation and Flood Control District, no local agencies have adopted any special floodplain policies to regulate development on alluvial fans. The policies adopted by Pima County are discussed in Section 8.2 of this report.

3.4 ADOT and the NFIP

The impact of the NFIP on ADOT'S responsibilities for highway planning and engineering can be discussed within the context of two programs:

- Federal-Aid Highway Program
- Non-Federal Highway Program

Highways that are planned and constructed with federal funds must comply with formal procedures established by the Federal Highway Administration (FHWA) to insure that such projects are consistent with the standards of the NFIP. There is no formal requirement to comply with these FHWA procedures on non-federally funded highway projects. The following subsections present a brief discussion of each program.

3.4.1 Federal-Aid Highway Program

The Federal-Aid Highway Program Manual, (November 15, 1979) Volume 6, Chapter 7, Section 3, Subsection 2, (FHPM 6-7-3-2) prescribes policies and procedures for the location and hydraulic design of highway encroachments in floodplains. The policies of this manual are stated as follows:

1. to encourage a broad and unified effort to prevent uneconomic, hazardous or incompatible use and development of the Nation's flood plains,
2. to avoid longitudinal encroachments, where practicable,
3. to avoid significant encroachments, where practicable,
4. to minimize impacts of highway agency actions which adversely affect base floodplains,
5. to restore and preserve the natural and beneficial floodplain values that are adversely impacted by highway agency actions,
6. to avoid support of incompatible floodplain development,

7. to be consistent with the intent of the Standards and Criteria of the National Flood Insurance Program, where appropriate, and
8. to incorporate "A Unified National Program for Floodplain Management" of the Water Resources Council into FHWA procedures.

Implementation of these policies requires the preparation of a "Location Hydraulic Study", which includes the following requirement:

> "Local, State, and Federal water resources and floodplain management agencies should be consulted to determine if the proposed highway action is consistent with existing watershed and floodplain management programs and to obtain current information on development and proposed actions in the affected watersheds."

Accordingly, there is no question that the Federal-Aid Highway Program places a strong emphasis on coordinating highway projects with all the agencies that might be impacted by such a project.

FHPM 6-7-3-2 also includes a section on Design Standards. Although these standards do not reference or include any special procedures to be used for alluvial fan locations, they also do not prescribe any specific technical methodology (i.e., HEC-1, HEC-2, etc.) that has to be used for the analysis and design of any highway project. Accordingly, the design engineer is free to exercise his best judgement in selecting a technical methodology that is most appropriate for a specific highway project. This gives the engineer ample latitude to vary his hydrologic/hydraulic design procedures to accommodate the change in flooding characteristics that might be encountered as a proposed highway alignment moves from a classic riverine environment onto an alluvial fan environment.

In 1982, the FHWA published a document entitled "Procedures for

Coordinating Highway Encroachments on Floodplains with the Federal Management Agency". Essentially, this publication supplements FHPM 6-7-3-2 by providing specific guidance on how highway project encroachments into floodplains and floodways are to be analyzed and coordinated with FEMA and local agencies in order to comply with NFIP criteria. This publication has been officially endorsed by FEMA (June 7, 1982) as providing "..... an excellent guideline for coordination between highway agencies, communities participating in the National Flood Insurance Program (NFIP) and FEMA, when flood plain encroachments involving highway construction are proposed".

In reviewing the floodplain policies established for Federal-Aid Highway Program projects, it is very clear that considerable emphasis has been placed on compliance with NFIP criteria and encouraging maximum coordination with all federal, state, and local agencies that might be impacted by such a project. From a technical engineering perspective, the prescribed procedures include flexibility that allows the engineer to select an analysis technique that he would consider to be most appropriate for the site under investigation (e.g., riverine or alluvial fan environment). As long as ADOT continues to comply with these policies, they will have a sound and effective basis from which to initiate planning and design studies for highway projects located in a floodplain environment.

3.4.2 Non-Federal-Aid Highway Program

Highway projects constructed in Arizona without financial assistance from the FHWA are not dutifully bound to comply with the procedures outlined in FHPM 6-7-3-2. However, as a practical matter, these federal procedures/guidelines present a very logical approach to the planning and construction of any highway system in a floodplain environment.

Recognizing the logic of this approach, ADOT personnel indicate that for non-federal-aid highway projects they make every effort to comply with NFIP criteria and employ a "good neighbor" philosophy in coordinating highway floodplain encroachments with local agencies that might be impacted by such projects. As with the Federal-Aid Highway Program, ADOT has no specific policy or engineering techniques for application to highway design on alluvial fans versus a riverine environment. They maintain the same flexibility provided in the federal program, i.e., the highway planners and engineers are free to select the most appropriate design methodology for the site under investigation. This is a common-sense approach that does not bind the engineer to one specific methodology that may only be applicable to limited environments.

ADOT presently employs what could be termed a "three-phase" process in the planning and design of highway projects. The first phase in this process is the preparation of a "Project Assessment" which identifies the project objectives and locates one or more alternative highway alignments. Since this report is reviewed by the ADOT Drainage Section, a qualitative assessment can be made of any potential floodplain/drainage problems that might accompany any of the preliminary alignments. This review can be used as justification for eliminating those alignment alternatives that would be expected to produce very severe floodplain encroachments or drainage problems.

The second phase consists of a "Design Concept Report" which defines specific design criteria and includes a relatively in-depth analysis of major drainage problems, such as those that might be encountered on an alluvial fan or in a riverine floodplain. A site-specific methodology is employed at this phase to: 1) quantify the severity and extent of the flooding problems; and 2) develop a plan that could be used to effectively eliminate these problems from being a potential source of danger to the proposed highway project. It is in this phase that the engineer has the flexibility of selecting an analytical technique that would most accurately simulate the floodplain characteristics of the location under investigation.

Phase three of this process is "Final Design". At this point all major floodplain/drainage problems should already be resolved. The only remaining task is to transfer the drainage plan into a set of construction drawings.

In summary, this three-phase highway planning process appears to be a practical approach to the design of non-federal-aid highway projects. It acknowledges the importance of complying with NFIP criteria and coordinating floodplain encroachments with local agencies. There are also no rigid policies which restrict the highway engineer from exercising good engineering judgement in selecting analytical techniques that are most suited for a specific project. If the engineer has an understanding of the basic fluvial processes associated with a specific site, he should have no problem working within the framework of either the federal or non-federal-aid program in developing a reasonable analysis of the floodplain problems associated with the site.

4 ROAD DAMAGE AND MAINTENANCE COSTS ON ALLUVIAL FANS

From a transportation system perspective, an important product of alluvial fan research would be to identify specific roadway problems that have historically been experienced on alluvial fans and to tabulate the cost associated with repairing such damage and/or implementing unique maintenance procedures to keep the system operational. In an attempt to gather such information, questionnaires were sent to the four ADOT District Engineers, all county highway departments, and several Arizona municipalities. The questionnaire requested information relative to: 1) the type of problem encountered; 2) the estimated annual maintenance cost to mitigate the problem; and 3) any maintenance program changes that have been implemented to eliminate or reduce damages to roadway systems on alluvial fans.

Unfortunately, a very limited response was received on this topic. This could be interpreted to mean that roadway damage on alluvial fans is very limited in Arizona, or that records are not kept to allow an agency to differentiate between alluvial fan and non-alluvial fan roadway problems. The following subsection summarizes the comments that were received for various components of a highway system.

4.1 Highway System Damage Categories

The following paragraphs pertain to comments received for the categories of roads, bridges, culverts, and grade crossings.

Roads

This category only pertains to the roadway surface/embankment. Comments received for this category of damage are summarized as follows:

* Washed-out roads
* Erosion of granite mulch backslopes
* Erosion and sedimentation
* Edge scouring and sediment deposition
* Rutting and erosion
* Roadways become channels when aligned parallel to fan drainage patterns.

The City of Tucson estimated an annual maintenance cost of $25,000 for this category of roadway damage, while Greenlee County estimated on annual cost of $300,000 for 359 miles of roadway. No maintenance cost data was received from any other agencies.

Bridges

No damage/maintenance data was received for this category other than a general comment of "erosion, scour and sedimentation".

Culverts

Comments received for this category are summarized as follows:

- Constricted openings create upstream watercourse aggradation.

- Reduced flow capacity due to sediment/debris deposition within the culvert and at the culvert inlet.

- Wash-outs and structural damage.

The City of Tucson estimates an annual maintenance cost of $75,000 for alluvial fan culvert installations, while Greenlee County estimates $30,000 per year for maintaining culverts dispersed through 337 miles of dirt roads. No annual maintenance cost data was received from any other agencies.

Grade (Dip) Crossings

Comments received for this category are summarized as follows:

- Sediment/debris deposition

- Standing water which renders the crossing impassable.

- Damage to asphalt paving.

- Scouring at pavement edge.

The City of Tucson estimates an annual cost of $20,000 to maintain grade crossings in alluvial fan areas, while Greenlee County estimates an annual cost of $15,000. No annual maintenance cost data was received from any other agencies.

4.2 General Comments/Recommendations

In an attempt to reduce or eliminate the problems presented in the preceding section, some agencies indicated the following actions were being pursued:

* Eliminate grade (dip) crossings.

* Design structures with more emphasis on erosion potential, i.e., cutoff walls and bank protection.

* Curb and gutter installations required along roads.

* On a case by case basis, flood control improvements may be required in conjunction with the road construction.

* Minor re-alignment of washes.

* General improvement in the overall quality of maintenance work.

* Closer control being exercised in the design and construction of roadway crowns, drainage channels, and berms.

* Install flood warning signs at grade crossings.

The type of roadway design and expected maintenance effort for alluvial fan environments should obviously reflect the level of service required for the area. For example, is the alluvial fan segment of the roadway part of the Interstate Highway system, or is it merely to provide local access for very sparse development. Perhaps one of the key design criteria might be whether the roadway could tolerate temporary closures during flooding conditions. If so, grade crossings might be a preferable alternative to culvert/bridge installations.

For those cases of roadway design that involve low traffic volumes to sparsely inhabited areas, some interesting data is available from an article entitled *"Alluvial Fans and Desert Roads – A Problem in Applied Geomorphology"*, by Asher P. Schick. This article documents recorded flood damage to roadways on alluvial fans in southern Israel. The data derived from this study were summarized by Schick as follows:

"(1) The road surface should stick to the original fan surface as closely as possible. Available evidence indicates that exposure to flood damage increases with vertical deviation of the road structures from the grade line.

(2) Sediment settling basins are ineffectual on arid alluvial fans. For all but insignificant flows, they are filled with sediment during the first minutes or even seconds of a flood. To make them effective, they must attain a capacity of at least one tenth of the total volume of some typical flood event. In the examples cited for the event of 12/2/72, this means 5–20 times larger settling basins than those that were in existence at that time. Big holes like that are difficult to dig, have to be re-excavated periodically, and might incur the wrath of nature lovers.

(3) In all cases examined in the framework of the project, bridgeless crossings were preferable to culverts. The crossings are, on the whole, less expensive, and entail a much smaller overall deviation from the grade surface of the fan. Further, it is possible to design them carefully in such a way that they will be (i) on the trace of the most probable flow lines; (ii) at a right angle to these flow lines; and (iii) vertically positioned slightly below the grade surface so that, during

flows, they will be covered by a thin veneer of sediment which helps to protect the road surface from erosion.

The above procedure requires the services of a proper geomorphic survey which has to precede the detailed planning stage.

In contrast to bridgeless crossings, culverts silt up easily, often require raised embankments, and entail the construction of lead ditches which are loci of lateral erosion.

(4) Drainage ditches running parallel to the roadway on its up-fan side do not serve any demonstrable purpose except for very small flows which can be dealt with routinely anyhow. A further disadvantage is the necessary periodic maintenance."

It should be emphasized that Mr. Schick's recommendations are for low-volume roadways where temporary closures (at dip crossings) can be tolerated. Obviously, the design of a major highway would require a different approach. However, the recommendations provided by Mr. Schick still provide beneficial guidance on the type of problems that should be anticipated in the roadway design, i.e., special provisions can be incorporated into the analysis/design effort to investigate sediment inflows for detention basin design, silting of culverts, and lateral erosion of drainage channels.

Within Arizona, some of the major problems encountered by the author in the analysis and design of roadway projects on alluvial fans, terraces, and bajadas are summarized as follows:

1. Due to the sheetflow characteristics of alluvial fans, it is often difficult to determine the proper location for a culvert crossing. Fan environments typically exhibit a dense braiding network of small

washes. It is not feasible to construct a culvert at the intersection of each of these washes; any attempt to do so would probably result in an uneconomically large number of culvert installations.

2. Due to the transient nature of braided flow patterns on alluvial fans, the ephemeral washes are prone to shifting alignments over a period of time. The occurrence of such a phenomenon may leave culvert crossings high and dry at some time after their construction.

   This shifting flow pattern can also create uncertainties in the design of roadway embankment heights that parallel or cut diagonally across the fan drainage pattern. For example, a roadway may be initially designed and constructed in an area of the fan that is not in close proximity to any major drainage channels; however, after five to ten years, the drainage pattern on the fan may have shifted towards the road, so that the road is now in direct contact with a major drainage conduit. This creates a potential failure mechanism to the roadway as the result of embankment erosion and/or overtopping.

3. The design of alluvial fan detention basins (upstream of roadways) can be complicated by the large sediment inflows generated on fans and by the relatively steep slopes normally found on fans. Steep slopes generate excessive excavation requirements in order to obtain any flood control storage. Headcutting also becomes a problem at the upstream end of the basins.

   Another critical factor in the design of alluvial fan detention basins is the problem of insuring that the transient flow pattern on the fan can be totally captured and routed into the basin. This may require the installation of a system of training dikes upstream of the basin.

4. The construction of drainage collector channels perpendicular to the fan drainage pattern can create substantial sedimentation problems if the sediment transport capacity of the collector channels is not capable of transporting the sediment inflows. This will almost always present a problem because of the natural decrease in slope that will occur as one moves from a down-fan direction to a transverse alignment across the fan. Such a slope reduction will create the potential for a velocity reduction and corresponding decrease in sediment transport capacity.

5. The design of culvert crossings will frequently be based on the interception of large areas of sheetflow or numerous channel braids. This presents a problem in trying to design a culvert that will be capable of passing the total sediment flows that are intercepted by the roadway and directed to the culvert entrance. If a proper design is not provided, the culvert will be susceptible to substantial sedimentation, which may degrade its design performance.

Each project encountered by the highway engineer will exhibit varying degrees of these problems, along with others that may be unique to each site. Although it is impossible to design the highway drainage system to be in equilibrium with all the flow events that may be encountered during the project life, serious impacts can be anticipated and provided for in the roadway design. An understanding of the hydraulic processes on alluvial fans can then be used to develop a complimentary maintenance program to deal with expected variations from the design conditions.

5 ENGINEERING AND REGULATORY PROBLEMS ON ALLUVIAL FANS

As suggested earlier in this report, it is the author's opinion that alluvial fans in Arizona have not historically been a source of major flood damage. This is attributed to the absence of any major development or highway encroachments on active fans in the State. This is in sharp contrast to the catastrophic damage that has occurred in neighboring states such as California (e.g., Rancho Mirage and Palm Desert).

However, as the rapid population growth in Arizona continues, alluvial fans, bajadas, fan terraces, and pediments are becoming more prone to urban development, along with the associated infrastructure of roads and utility services. In order to prevent the occurrence of tragedies such as those experienced in California, it will behoove all regulatory agencies in Arizona to become intimately familiar with fan characteristics so that poorly planned developments will not be allowed to occur on fans in Arizona.

Some communities in Arizona are already beginning to experience development pressure into alluvial fan environments. For example, the City of Scottsdale is presently developing a General Drainage Plan for the McDowell Mountain/Pinnacle Peak area, which contains numerous fans and a broad alluvial fan terrace. Pima County is currently formulating a Management Plan for fans in the Tortolita Mountains.

In order to gain direct input on the engineering and regulatory problems being encountered in such environments, numerous regulatory agencies (municipalities, counties, etc.) in Arizona were provided with questionnaires soliciting their response to specific issues regarding development on alluvial fans. The questions addressed the application of NFIP criteria to alluvial fan development, as well as the effectiveness of local floodplain policies and technical procedures presently in use on alluvial fans. The response to these questions is summarized in the following subsections of this report.

One difficulty perceived by the author during a review of the questionnaire responses was the way in which an alluvial fan was being interpreted by the questionnaire respondents. It appeared that some responses were oriented to general drainage problems (that could occur anywhere) rather than to the unique environment of an alluvial fan.

5.1 NFIP Problems on Alluvial Fans

Comments on problems in the application of NFIP criteria to alluvial fans was requested for the following categories of construction: 1) private development; 2) roads; 3) bridges; 4) culverts; 5) drainage/flood control; and 6) utilities. Of the 19 questionnaire respondents, 9 indicated problems with private development, 7 had problems with roads, 5 encountered difficulties with bridges, 7 had problems with culverts, 6 indicated conflicts with flood control/drainage projects, and 4 agencies stated that utility services were a problem area when constructed on alluvial fans using NFIP criteria.

Typical comments representing the problems perceived by the agencies are summarized, and in some cases quoted, as follows:

* "Compliance for this program is considered too much red tape and expensive by many of the residents and developers."

* The use of AO zones with average depth classifications is considered unrealistic and overly conservative in establishing minimum finished floor elevations relative to existing land elevations. FEMA alluvial fan methodologies derive depth numbers which assume the formation of an entrenched channel below existing land grade and incorporate velocity head into a derivation of total depth.

* Difficulties are encountered in conducting scour analyses and modeling existing runoff patterns. Local engineers are not well-versed in alluvial fan characteristics.

* Uncertainties in defining the 100-year floodplain to establish building envelopes for private development on alluvial fans. Variable flow patterns and difficulties in predicting geomorphic response

upstream and downstream of developments.

* "People wanting to enlarge existing structures in designated floodways."

* "Generally, private development suffers from lack of specific information and expertise to cope with design problems and to recognize the need for caution. Public development has serious difficulty funding the relatively large projects for the relatively low probability flood episodes; relative to say, roads, sheriff, etc. which generally function daily."

* Geomorphic features that have caused problems in the presently urbanized areas of Maricopa County have not been due to alluvial fans. We have experienced problems with high sediment loads in streams, or overland flow emanating from undersized, but relatively stable channels. However, we believe this is a condition indicative of an arid pediment, presenting physical conditions significantly different than to those of alluvial fans."

* "The floodplains are very wide and have been delineated using empirical methods that are either obsolete or without application of engineering judgement and practical considerations. The economics of scale are sometimes absent."

* "Difficulty in determining drainage area; difficulty in determining flow splits for varying frequency. Drainage facilities frequently experience aggradation problems upstream and degradation problems downstream."

* "The main overall problems stem from the poor quality of our Flood Insurance Rate Maps, which tend to include far too much area in the regulatory zone. The lack of adequate crest elevations makes it expensive and risky to obtain LOMAs. We are trying to get ADWR to help improve elevation control."

* "FIRMS do not always indicate where flooding may occur. Public does not accept floodplain boundaries and does not understand the shifting nature of alluvial fan flood flows."

* "In general, because of the diversity of alluvial fan processes and the mixture of inactive and active areas on a given fan, the NFIP rules should be more flexible, and yet demanding of site-specific data collection and analysis. One model and one set of NFIP rules will be insufficient and inappropriate to regulate development.
One problem that has arisen from NFIP policies in the San Diego area is that, in areas of coalescing fans, flood hazard zones are juxtaposed against other zones in a manner that cannot be justified on a hydrologic basis. For instance, a Zone AO3 might lie adjacent to a Zone AO1, without there being any drainage divide or other topographic feature to influence the depth of flow."

5.2 Local Floodplain Policies Adopted for Alluvial Fans

An indication of the severity of alluvial fan problems in Arizona should be reflected in the number of local floodplain policies adopted to address the unique flooding characteristics of fans. Such policies might also be expected to fill "gaps" or deficiencies in the NFIP/FEMA policies. As before, the questionnaire was used as the primary data source to retrieve information from regulatory agencies relative to special floodplain policies adopted for the alluvial fan environment.

Of the 17 public agencies that responded to this question, only one agency (Pima County) had written guidelines prepared for an alluvial fan environment (*Tortolita Fan Area Interim Floodplain Management Policies*, see Section 8.2 of this report for detailed discussion). LaPaz County indicated a general policy of avoiding development on alluvial fans, and requiring "mitigation and floodproofing" when avoidance was not possible.

Nine of the 17 public agencies thought their current floodplain policies were adequate for alluvial fans, while 3 agencies stated their policies were not adequate, and 6 agencies indicated they did not know the effectiveness of their policies or that alluvial fan policies were not applicable to their area of jurisdiction.

The following comments are typical of those received in response to a question asking for recommendations on how an agency's current policies could be improved.

- "More experience with projects on alluvial fans. Develop design standards for stormwater collection, sedimentation basins, and channel construction in terms of erosion control."

- Supplement drainage policies and practices, that rely on avoidance, mitigation, and floodproofing, with the construction of public works projects (improvements) to enhance the hydraulic capacity of floodways.

* "Consider the mapping of erosion hazard zones based on geomorphic assessment."

* "What we need are improvements to existing washes."

* "Identification of diffused drainage patterns, both in terms of soil characteristics and forces that need to be dissipated in the flowing waters would help. Regional detention facilities seem to be an answer, but this needs to be justified further."

* Conduct master drainage studies.

* "The policies seem sound, but the maps (FIA) themselves do not go far enough in assuring fairness for an individual property owner."

* "Improved FIRMS".

5.3 Local Technical Procedures for Alluvial Fan Analyses

Of equal importance as floodplain policies, are the technical procedures that are used by engineers to conduct hydrologic, hydraulic, and sediment transport calculations for the analysis of alluvial fan developments. The chances of an alluvial fan drainage system operating as intended will only be as good as the design calculations are in simulating the actual physical behavior of the processes at work on a fan. Conventional analysis techniques that have traditionally been used in more stable riverine environments may not be totally applicable to an alluvial fan or may have to be used with revisions and/or substantial engineering judgment.

Discussions of specific technical methodologies that may be applicable to fan environments are presented in Section 6 of this report. However, in order to obtain specific information on any innovative methods being used by regulatory agencies in Arizona, the questionnaire requested such agencies to describe the analytical procedures that they presently employ for the analysis of alluvial fans.

Of the 17 public agencies responding to this question, none indicated that they had adopted any specialized technical procedure for the analysis of alluvial fans. It should be noted that the majority of the questionnaire respondents indicated that they rely on the accuracy of technical studies prepared by registered engineers.

Eight of the 17 agencies felt their current procedures accurately simulated the behavior of an alluvial fan, while five agencies felt they did not, and four agencies had no comment on the technical accuracy of their procedures in an alluvial fan environment.

Nine of the public agencies also offered suggestions on how they felt their current technical procedures could be improved to better simulate the analysis of alluvial fan problems.

Typical comments received in response to the question on technical procedures are summarized as follows:

- Commonly used computer models, such as HEC-1 and HEC-2, do not address sediment transport. Agency procedures should be revised to require the use of a sediment transport model. A design manual should be created for engineers to follow when working on alluvial fans.

- Accurate input (field) data is often difficult to obtain. This causes uncertainty in the accuracy of the analytical results. "Recommend that: 1) additional data be collected to properly assess input parameters for a procedure; and 2) develop procedures in which a large amount of cross-sectional data can be accommodated and easily edited."

- Current procedures are not accurate and "are generally independent of each other. No comprehensive analysis is done on <u>whole</u> watershed system. Each part is studied only enough to satisfy FEMA and local requirements for that project only."

- "For master planning we have utilized diffusion modeling (as developed by Guymon and Hromadka) as a tool to predict flow paths for the East Fork of the Cave Creek Study and assessment of flow paths below the spillways for the structures we maintain."

- "Develop a procedure to relate all construction within fans to a future floodway designation which would eventually be FEMA designated Floodways."

* Street patterns for urbanized areas are "evaluated to ensure that the water flows radially down and across the intersections. Side streets must be designed to contribute to streets radially flowing out...... masterplanning, identifying locations of regional detention facilities and accurately determining the hydrology may be a start to identifying solutions for such hazard areas."

* "Assumption of gradually varied flow and rigid boundaries is not applicable". (Note: This comment was made in reference to an agency's use of HEC-2 and WSPRO.)

* "Standard hydraulic procedures are usually adequate for design on alluvial fans where the channels are deeply and permanently (in the human time frame) incised into the alluvium. ..... In active fan environments, these procedures inadequately describe the location, velocities and depths of flooding. In an active fan, one cannot assume that the next flow path will be the same as the last. Engineers need much more familiarization with alluvial fan processes. We have seen substantial confusion arise simply because inactive and active fans are not distinguished. ..... Analyzing the past history of alluvial fan flooding is important to know what kind of assumptions are reasonable for modeling."

* "Development on alluvial fans, if done correctly, will ultimately result in an orderly, fixed alignment for primary channels which traverse the fan, thus eliminating the bulk of unique, flood hazards associated with alluvial fans. However, development occurs in a piecemeal manner. This necessitates a conservative approach to establishing requirements for drainage improvements and FFE (finished floor elevations) that provides flood protection in the interim while

fitting into the long range drainage plan. Thus, procedures used for evaluating conditions for development purposes are (should be) conservative and probably not representative of actual flood potential and conditions."

Note: The following comment was made by the same individual in response to a question soliciting recommendations for improvements to current procedures. In this case, the individual is referring to the FAN computer model developed by Dave Dawdy for FEMA.

- "A more finite, precise approach that eliminates the need for conservatism probably goes beyond the scientific ability to predict the impacts of future flooding events. There are too many sediment related variables which would need to be considered that are beyond our ability to control or predict".

5.4 Critique of Alluvial Fan Regulatory Environment in Arizona

Due to the absence of any substantial historical flooding problems/damages on true, active alluvial fans in Arizona, both state and local regulatory agencies have been slow to address the specific needs for these environments. This is supported by the fact that only one regulatory agency (out of 49 agencies/individuals who were provided with research questionnaires) in Arizona has adopted a policy dealing with a specific alluvial fan problem. In the absence of such policies, agencies are relying upon the technical expertise and judgement of professional engineers to prepare engineering studies for such environments that will acknowledge the unique, site-specific characteristics of individual fans.

Because of limited exposure to alluvial fan problems, it is probable that the majority of engineers engaged in the design of urban development on alluvial fans are not fully cognizant of the extreme complexity of the environment in which they are involved. Failure to acknowledge and understand the dynamic behavior of the fluvial processes at work on a fan can lead to costly design errors.

As alluded to earlier in this report, this lack of engineering expertise can partially be traced to the heretofore minimal activity that has occurred on fans in Arizona, i.e., it has not been a subject that many engineers have had an opportunity to be exposed to. Compounding the problem is the fact that many planning and zoning commissions are often composed of non-technical personnel who have even less understanding of the geomorphic problems associated with alluvial fans than do engineers. If the engineer preparing the study and the commission approving the study are both less than completely familiar with fan behavior, the probability of achieving a well-planned development are somewhat remote.

An evaluation of the effectiveness of present management and technical methodologies for true alluvial fans in Arizona is difficult to make in the absence (with one exception) of any special policies that are oriented towards this problem. As stated previously, most agencies seem to rely on the judgement of professional engineers to accurately incorporate alluvial fan characteristics into any private development or roadway design; no special agency regulations are available that requires the engineer to address specific problem areas on a fan. Additionally, there are no special technical procedures that are required by an agency when an engineer is pursuing development on a fan; engineers are essentially left to select the methodologies they feel most appropriate for the project.

As development on fans, terraces, and pediments increases, regulatory agencies are going to find that the lack of specific planning policies and technical procedures for such areas will lead to poorly planned developments that are exposed to a high risk of flood damage. It is the author's opinion that agencies should develop master planning studies for these environments and establish technical guidelines that the engineer can use as a checklist to insure that the project design acknowledges the hydrologic, hydraulic, erosion, and sediment transport issues that are characteristic of these environments. Hopefully, through additional research, some improved methodologies might be available in the future which could be adopted by agencies for use in these environments. This should not be interpreted, however, to infer that an acceptable analysis of alluvial fan characteristics is impossible at the present time. If one understands the basic processes at work on alluvial fans, sound engineering judgement can be combined with presently available technical procedures to successfully design urban developments and transportation systems on alluvial fans, terraces, and pediments.

There is substantial evidence that several regulatory agencies in Arizona are aware of the need for these special policies. As mentioned previously, Pima County has already adopted "*Interim Floodplain Management Policies*" for the Tortolita Fan Area Basin. The City of Scottsdale initiated work (January 1988) on a "*General Drainage Plan For the North Scottsdale Area*"; this area includes several alluvial fans and a fan terrace, all of which will receive special consideration during development of the drainage plan. The Flood Control District of Maricopa County has developed several "Area Drainage Master Studies" for portions of Maricopa County. Mohave County is presently involved in the design and construction of a comprehensive flood control plan for the Bullhead City area.

The Arizona Floodplain Management Association (AFMA) has also taken an active role in attempting to educate its membership on the problems encountered in the arid watersheds of the Southwest. AFMA frequently sponsors guest speakers at its meetings to address these topics.

Although the "Tortolita Fan Interim Floodplain Management Policies" is apparently the only instance of a formal agency policy specifically oriented towards an alluvial fan in Arizona, it appears that the need for these type of speciality studies/procedures is beginning to be recognized. Hopefully, this trend will continue in the future, and Arizona will be spared the experience of a "Rancho Mirage". To accomplish this goal, continued emphasis should be placed on educating regulatory agencies and technical professionals on characteristics and analytical procedures appropriate to alluvial fan analyses. Technical research should also be continued in order to improve the methodologies that are available for use on alluvial fans.

6 TECHNICAL PROCEDURES FOR ANALYZING ALLUVIAL FANS

One of the objectives of this research report is to "evaluate effectiveness of present management and technical methodologies in mitigating flood hazards in alluvial fan areas." Section 5.2 of this report discussed the floodplain policies (or lack thereof) presently being used to manage the development of alluvial fans in Arizona, while Section 5.3 reported no regulatory agencies in the State have presently adopted any specialized technical procedure for the analysis of alluvial fan processes.

In the absence of locally adopted procedures (with the exception of the Tortolita Fan Area), the author has conducted an extensive literature search to document technical methodologies and management practices that may have some application to either all or some portion of an alluvial fan. Section 6 presents a detailed discussion of these technical procedures, while Section 7 presents a review of alluvial fan management practices. This information is provided in order to give the reader a broad range of views on how the alluvial fan problem has been approached by other engineers, researchers, and federal agencies.

Some of the technical methods in Section 6 are more applicable than others. A synopsis of each method is provided along with a reference to the original article. The reader is encouraged to obtain the original article if more detailed information is desired.

6.1 FEMA Procedure

Perhaps the most widely known procedure for conducting a hydraulic analysis of alluvial fans is the methodology adopted by FEMA and presented (as Appendix 5) in a publication entitled *"Flood Insurance Study Guidelines and Specifications for Study Contractors"*, Federal Insurance Administration, September 1985. The methodology presented in this publication was originally developed by Dawdy (1979) and subsequently modified in response to a report prepared by DMA Consulting Engineers (1985).

As the title suggests, this procedure was developed to delineate floodplain limits on alluvial fans. Accordingly, it does not provide procedures for developing design parameters for the construction of roads or commercial/urban structural improvements on fans.

Description of Methodology

The FEMA procedure was developed to provide a standardized technique for indentifying "Special Flood Hazard Areas" on alluvial fans. These areas are classified as "Zone AO", which is defined as follows:

"Zone AO is the flood insurance rate zone that corresponds to the areas of 100-year shallow flooding (usually sheet flow on sloping terrain) where average depths are between 1 and 3 feet. Average whole-foot depths derived from the detailed hydraulic analyses are shown within this zone."

The adopted procedure relies heavily on empirical equations relating depth and width of flow to discharge. Knowing these two relationships, an equation can also be developed relating channel velocity to discharge. Specifically, the geometry of the alluvial fan channel is based on field evidence that the channel will stabilize (i.e., lateral erosion of the banks will cease) at a point where a decrease in depth causes a two-hundred fold increase in width. Based on this field data, Dawdy (1979) developed the following equations:

$$W = 9.5Q^{0.4} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6.1)$$

$$D = 0.07Q^{0.4} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6.2)$$

where W = channel width (ft.)
D = channel depth (ft.)
Q = discharge (cfs)

Assuming a rectangular channel, and knowing that $Q = AV$, Equations 6.1 and 6.2 can be used to derive a relationship between velocity and discharge:

$$Q = 0.13V^{5} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6.3)$$

where Q = discharge (cfs)
V = velocity (fps)

When using this method, these three equations form the basics for describing single channel hydraulics on an alluvial fan.

In order to use these equations, information relative to the discharge at the fan apex must be known. The FEMA procedure requires a complete flood discharge-frequency distribution using log-Pearson Type III (LP III) analyses as presented in United States Water Resources Council Bulletin #17B. Bulletin #17B prescribes procedures to be used for the statistical analysis of stream gage data. Unfortunately, very few (if any) alluvial fans containing stream gages will be found in Arizona. Accordingly, in most cases, procedures other than stream gage analyses will be required to determine the discharge-frequency relationship at the apex of a fan. Such procedures might take the form of computerized rainfall-runoff modeling (HEC-1), or regionalized peak discharge regression equations.

Once an appropriate peak discharge methodology has been selected and the discharge-frequency relationship established, the LP III statistical parameters (skew coefficient, standard deviation, and the mean of the logarithms of the computed discharge values) must be computed using relationships presented in the FEMA publication. These parameters are then used to compute the LP III transformation variables and a transformation constant. These statistical parameters are ultimately used in the computation of the fan widths (i.e., arc lengths from one side of the fan to the other) that define the floodplain boundaries for specific depth/velocity zones on the fan.

For a <u>single</u> channel region of the fan, the following relationship is employed:

$$\text{Fan Width}_{sc} = 950ACP \quad (6.4)$$

where A = an avulsion coefficient (to be discussed in subsequent paragraphs)

C = LP III transformation constant

P = probability of occurrence of the discharge that corresponds to a selected depth or velocity of flow

Working within the framework of Equations 6.1 through 6.4, the basic operation of the FEMA procedure is summarized in the following steps. The same procedure is applied to both upper and lower boundaries of a "depth zone" (e.g., for a depth zone of 1.0 foot, the lower boundary is 0.5 feet and the upper boundary is 1.5 feet) and a "velocity zone".

1. Using an appropriate hydrologic methodology, compute the peak discharge for the 100-, 10-, and 2-year floods at the fan apex.
2. Using the discharge values from Step 1, compute the LP III statistical parameters.
3. Select a flood zone depth, for which a fan width is desired, that has a 1% annual probability of being flooded, (e.g., 0.5 ft, 1.5 ft, 2.5 ft, etc.)
4. Using Equation 6.2, compute the discharge corresponding to the depth selected in Step 3.
5. Using the LP III parameters from Step 2, compute the probability of occurrence of the discharge computed in Step 4.
6. Use Equation 6.4, along with the statistical data from Steps 2 and 5, to compute the fan width for the assumed conditions.
7. Use a topographic map to find a fan arc (contour line) that fits the width computed in Step 6. This arc then establishes a boundary limit (i.e., upper or lower, depending on the initial selection) for the flood depth zone being analyzed.
8. Steps 1 through 7 are repeated for all the flood depth zone boundaries (probably 0.5 feet through 4.5 feet, at 0.5 foot intervals) desired for the fan.
9. A similar procedure is then used to identify velocity zone boundaries. However, velocity zone calculations utilize Equation 6.3, rather than Equation 6.2, to determine the discharge value in Step 4.
10. The depth and velocity zones computed from these procedures are used to delineate specific boundaries on the fan that enclose areas of similar depth/velocity combinations.

As indicated previously, the 10 steps outlined above are only intended to illustrate the basic procedure used by FEMA for alluvial fan analyses. The <u>complete</u> procedure contains modifications (based on the 1985 DMA study), to address channel bifurcations that essentially divide the fan into regions of both <u>single</u> channel and <u>multiple</u> channel flow. The boundary of these two regions is based on an empirical relationship between the length of the single channel region and the ratio of the canyon slope to the fan slope. A decrease in this ratio causes an increase in the length of the single channel region.

The multiple channel region also uses a different set of equations to determine the depth and velocity zones. The following relationships are used for the multiple channel region:

$$D = 0.0917 n^{0.6} S^{-0.3} Q^{0.36} + 0.001426 n^{-1.2} S^{0.6} Q^{0.48} \quad \ldots\ldots\ (6.5)$$

$$Q = 99{,}314 n^{4.17} S^{-1.25} V^{4.17} \quad \ldots\ldots\ (6.6)$$

where D = total flow depth (ft) due to pressure head & velocity head
V = velocity (fps)
Q = discharge (cfs)
n = Manning's roughness coefficient
S = alluvial fan slope (ft/ft)

The fan width in the multiple channel region is:

$$\text{Fan Width}_{MC} = 3{,}610\,ACP \quad \ldots\ldots\ (6.7)$$

where A, C, and P are as defined for Equation 6.4.

An important distinction between these two flow regions (single channel vs. multiple channel) is the assumption that critical depth prevails in the single channel area on the upper reaches of the fan, while normal depth exists in the multiple channel region on the lower part of the fan.

In addition to providing guidelines on the analysis of adjacent, coalescing alluvial fans, the procedure also incorporates a mechanism to address channel avulsions. This phenomenon (avulsions) is an abrupt change of flow path across an alluvial fan. This is caused by debris, mud flows or sediment deposition that may cause total or partial blockage of a channel during a flood event. When this occurs, the flow path will be diverted to a different portion of the fan, where a new channel will begin to form. The continuing process of avulsions (over geologic time), is the mechanism that causes the uniform distribution of sediments that builds the fan into its classic conical form.

Consideration of avulsions is included in the FEMA procedure because avulsions cause a significant increase in the probability of flooding at any point on the fan. This increased probability occurs because of the potential for the flow-path to occupy multiple positions on a fan during a specific flood event, i.e., a channel may avulse halfway through a flood and occupy a new alignment for the remainder of that specific flood event.

The potential for avulsions is acknowledged in the fan width calculations (Equations 6.4 and 6.7) by including an avulsion coefficient. A coefficient greater than 1 would indicate that the specific fan under study has some degree of avulsion potential. A value of 1.5 is recommended in the absence of other data. Use of this value assumes that an avulsion will happen with the occurrence of every other 100-year flood (DMA, 1985).

Comments on Methodology

As stated previously, the FEMA procedure was developed specifically to delineate "Special Flood Hazard Areas" (AO Zones) for use in flood insurance studies. As a result, the procedure does not include provisions for addressing sediment transport issues that may be crucial to the design of a specific structure or development on an alluvial fan. Furthermore, it only addresses the flooding potential of runoff that is delivered to the apex of the fan, i.e., it does not include the flood potential from rainfall falling directly onto the fan surface.

The procedure also excludes any mechanism to examine the attenuation and translation of a hydrograph as water flows from the fan apex to the toe.

In reviewing this procedure, the author would also urge caution in developing synthetic LP III parameters when no stream gage data is available at the fan apex. In the absence of gage data, the calculation of synthetic peak discharge data will strongly influence the LP III statistical parameters that are computed from such data. The user will get different statistical parameters, and subsequently different arc lengths for the depth-velocity zone widths, depending on the peak discharge that is used at the fan apex. Under such conditions, it would be important for the user to pay particular attention to the results obtained from any synthetic hydrologic modeling procedures in order to verify that the peak discharges obtained from such procedures are indeed representative of the upstream watershed.

For general verification purposes, the FEMA procedure might consider the addition of some mechanism that could be used to check the realism of the predicted depth/velocity zones (computed from Equations 6.2, 6.3, 6.5, and 6.6) as a function of the peak discharge used at the fan apex. For instance, if Manning's equation were applied to the apex discharge, with a flow depth equal to that in a previously computed depth zone, would the resulting channel width and flow velocity be realistic? Through an iterative process, such a procedure could also be used to determine the hydraulic geometry required to produce a flow velocity equal to those predicted for a specific velocity zone. Simple continuity checks, such as these, might serve to minimize the possibility of gross inconsistencies between realistic hydraulic parameters and selected peak discharge data. However, an admitted limitation of such a procedure would be the failure to reflect a reduction in down-fan peak discharge due to transmission losses and hydrograph attenuation due to channel storage effects.

The user of the FEMA procedure should also be cautioned that the methodology does not acknowledge the vertical element of the fan topography, i.e., there may be small hills that are elevated sufficiently above the fan surface so that they would not be subject to the floodwater inundation limits described by the depth-velocity zones produced by application of this procedure.

An in-depth examination and critique of this procedure has been undertaken by French (1984). The primary criticism presented in the French report focuses on the validity of using Regime Theory (Equations 6.1, 6.2, and 6.3) to evaluate channel hydraulics on an alluvial fan. As a possible alternative, French suggests use (with some modifications) of the minimum stream power hypothesis presented by Chang and Hill (1977) and Chang (1982).

Modifications are recommended to: 1) address infiltration losses; 2) account for unsteady water flow and unsteady sediment supply; 3) address the validity of the minimum stream power concept at supercritical flow: and 4) develop a more technically defensible treatment of the criteria used by Chang (1982) to evaluate channel bank stability.

French also notes the inability of the FEMA procedure to address the impact of debris flows on the upper portions of a fan. Debris flows are considered to possess substantial damage potential. Very similar phenomena, mudflows and mud floods, can also cause tremendous damage on fans. In the spring of 1983, severe mudflows inundated portions of alluvial fans along a 30 mile length of the Wasatch Front Mountains in Utah. The damage from these mudflows, and efforts to reproduce the events through numerical modeling, are documented in a report published by the Corps of Engineers (1988) (see Section 6.8.2 of this report). Damage from both mud floods and mudflows are covered by FEMA under the National Flood Insurance Program, however, there have been disputes over damages from mudflows because of difficulties encountered in distinguishing mudflows from other types of hyperconcentrated flows. FEMA has defined Flood Hazard Zones "M", "N", and "P" for use in delineating areas of mudslide hazard (see Table 3.1 in this report).

It should be noted that the French report was based on a critique of the FEMA procedure as published in July 1983. The September, 1985 FEMA procedure contains revisions to address both single and multiple channel segments. These revisions to the original Dawdy procedure were based on the results of a 1985 study prepared by DMA Consulting Engineers for FEMA. The DMA study was commissioned to address two key assumptions in Dawdy's original work. These assumptions were;

1. the location of any stream channel on a fan is random; i.e., it has an equal probability of occurring anywhere across the fan;

2. the flow forms its own channel and remains in one channel throughout the flow event (with the exception of avulsions, which are accounted for by the avulsion coefficient)

DMA completed this study by undertaking an analysis of historical flood data from several alluvial fans in the southwestern United States. The data base developed for this study included aerial photographs of each fan before and after a recorded flood event. An extensive review was also made of the Anderson-Nichols (1981) study that had previously been prepared for FEMA (see Section 7 of this report).

The results of the DMA study support Dawdy's first assumption of a random stream channel location on the fan, but indicated that the single channel concept for the entire length of the fan was not realistic. Accordingly, revisions were recommended to modify the original procedures to include both the single and multiple channel regions. These revisions include the previously referenced equations (6.5, 6.6, and 6.7) for determination of the depth-velocity relationships and fan width in this region, as well as the empirical data for estimating the length of the single channel region.

The DMA data also indicated that Equation 6.1 provides a reasonable estimate of the width of a single channel on an alluvial fan. This conclusion was based on an analysis of 11 fans. Using the data from four fans, a conclusion was also reached that the total width of multiple channels across the fan width, for a given radius from the apex in a split channel region, was found to be 3.8 times the channel width in a single channel region. This rather small data base was used to develop the numerical coefficient in Equation 6.7 . The reader will note that the ratio of Equation 6.7 to Equation 6.4 is 3.8 .

No changes were recommended by DMA relative to the default avulsion coefficient of 1.5 . This was based on the fact that insufficient flood data was available to make such a recommendation.

Application in Arizona

FEMA was requested, by the author, to provide a list of alluvial fan sites in Arizona for which the published fan methodology has been applied. FEMA's response (written communication from John L. Matticks, Federal Insurance Administration, March 7, 1988) stated that "no effective Flood Insurance Rate Map was prepared based on a detailed flood analysis using the alluvial fan methodology for any community in Arizona." However, the author is personally aware of the FEMA fan procedure having been applied on the Tortolita Alluvial Fan in Pima County. In fact, this site is presented as a case study in this research report. This site was probably omitted from Mr. Matticks' letter since the effective FIRM has not yet been approved for this site. Conversations with a local engineering consultant also verified that a Flood Insurance Study for the Bullhead City area also used the FEMA fan procedure. No other applications of this method in Arizona are known to the author.

Application of the FEMA alluvial fan procedure to the Tortolita Fan has generated considerable controversy. In fact, the Pima County Department of Transportation and Flood Control District formally appealed the study to FEMA on March 3, 1987. The appeal is based on allegations that the procedure is "scientifically deficient in light of new and previously unavailable data regarding activity of alluvial fan processes in the study area" and "technically deficient when examined in relationship to the technical guidelines issued by FEMA and the alluvial fan flooding literature cited by FEMA."

The appeal is well-documented and raises several valid issues which challenge the accuracy of the Flood Insurance Rate Maps (FIRM). As with any pioneering methodology (especially one that deals with such a complex and dynamic environment as an alluvial fan) engineering judgement is required to ensure that application of the methodology will produce realistic results. It is within this framework that the appeal seeks revision of the FIRMs for the Tortolita Mountain fans. The basis of the appeal touches on several issues of which the practicing engineer should be aware, whether FEMA's' or some other procedure is being used for an alluvial fan analysis. Accordingly, the following paragraphs are devoted to a brief discussion of the contested technical issues in the *Tortolita Alluvial Fan Flood Insurance Study*

1. An extensive geological investigation was conducted to identify active and inactive portions of the alluvial fans. Based on the age of soil deposits, Pima County defined an active fan area as one which has been subjected to at least one alluvial fan flooding event in the last 10,000 years. Those areas which did not meet this criteria were considered inactive.

This is an important distinction which is used in the appeal to identify areas on the fan that are sufficiently elevated above the present day channels emanating from the mountain front and onto the alluvial fan surface. These areas are considered inactive and not subject to classic alluvial fan flooding processes, (at least within the last 10,000 years) because they are no longer hydraulically connected to the "trunk stream" that carries water from the mountain watershed onto the fan. Accordingly, an argument is made that inactive fan areas should not be mapped with the FEMA alluvial fan flooding procedure. The appeal notes that inactive fan areas are subject to flooding, but only from runoff generated on the inactive fan surface, not from the mountain watershed which feeds the fan.

2. The location of the alluvial fan apex is a critical factor in the application of the FEMA procedure. The apex location essentially dictates where the upstream end of the "AO" flooding zones will begin to be delineated. The Tortolita fans contain several deeply entrenched channels that, in some cases, extend several thousand feet downstream of the mountain front where the study contractor had located the majority of the fan apices. These channels exhibit sufficient capacity and bank stability to adequately convey the 100-year flood with substantial freeboard. Additionally, the age of the surrounding soil deposits indicated no evidence of recent (within the last 10,000 years) overbank flooding.

Based on this evidence, a valid argument is made that the areas adjacent to the entrenched segments of such channels are not subject to the "AO" depth/velocity zones that result from the FEMA alluvial fan procedure. Instead, the appeal recommends that the fan procedure be initiated at an apex location corresponding to the point at which the channel entrenchment begins to lose definition, i.e., the point at which the flow is not longer confined by channel banks and is thus allowed to spread across the fan surface. This point is commonly located near the middle part of the fan and has been defined by Hooke (1967) as the "intersection point".

3. The depth/discharge relationship for the single channel region (Equation 6.2) has been rearranged in the 1986 FEMA publication so that discharge is determined as a function of depth. The appeal claims that the coefficient of 0.07 in Equation 6.2 was rounded to approximately 0.1 when this mathematical manipulation was performed. This round-off assumption causes a substantial change in the coefficient for the transformed equation. If the original coefficient of 0.07 (Equation 6.2) is carried through the mathematical transformation, the resulting equation is:

$$Q = 771 D^{2.5} \quad (6.8)$$

As published in the 1985 FEMA manual, the transformed equation is:

$$Q = 280 D^{2.5} \quad (6.9)$$

The coefficient of 280 in Equation 6.9 will be obtained if the original coefficient of 0.07 in Equation 6.2 is changed to 0.105. Obviously, a substantially different result will be obtained when using Equation 6.8 instead of Equation 6.9. The use of Equation 6.8, which would appear to be the more correct relationship, will result in narrower fan flood widths (Equation 6.4) than those obtained using Equation 6.9.

Accordingly, based on this mathematical analysis, it appears that the single channel widths of probable fan flooding zones computed using the equation in the 1985 FEMA manual will be in error.

4. The 1985 FEMA publication provides guidelines for addressing the flooding potential on coalescent fan areas. These guidelines state that "separate depth-frequency relationships should be developed for each source of flooding and combined based on the probability of the union of independent events. The Pima County appeal alleges that these guidelines have been misapplied to the Tortolita Fan Area and have generated zones of depth-width (velocity?) values that are greater in the coalescent areas than on the adjacent single fan areas. The appeal argues that such a condition is unrealistic.

It would appear to the author, however, that if two overlapping (coalescent) fans were to flow simultaneously, there would be more floodwater involved than if only a single fan were flowing. Under such circumstances, it would appear logical to expect deeper flow depths and higher velocities in the overlap area than in the adjacent areas that are only receiving water from a single fan.

This summary discussion of the *Tortolita Alluvial Fan Flood Insurance Study* demonstrates the need for: 1) thorough field inspections of a study area; 2) familiarity with fan flooding characteristics; 3) the application of sound engineering judgement to the technical analysis; and 4) a thorough review of study results to insure that realistic answers are being obtained.

6.2 Edwards and Thielmann Procedure, Cabazon, California

Cabazon is a community of scattered residential development located northwest of Palm Springs in Riverside County, California. Floodplain maps published in 1973 and 1974 delineated very generalized, broad floodplain limits on the alluvial fans surrounding this community. These maps did not designate floodway limits or contain any information on depth and velocity of flow. As a result, this information was inadequate for community officials to make land use decisions or to develop design criteria for proper flood-proofing measures. To overcome this deficiency, an engineering study was commissioned which resulted in the development of land use guidelines and recommended flood-proofing criteria. The results of this study, which are summarized below are presented in a report by Edwards/Thielmann (1982).

Development of Methodology

In recognition of the unique flooding characteristics of an alluvial fan, the consultant conducted a literature search in order to identify a technical methodology that would be appropriate for such an environment. This resulted in the selection of the FEMA procedure (Section 6.1) that was developed by Dawdy (1979). However, since the FEMA procedure is oriented towards the identification of probabilistic depth-velocity zones, that are used to establish flood insurance rates, revisions to the procedure were required in order to more realistically analyze engineering problems that must be addressed when working in such an environment.

The FEMA procedure assumes the probability of flooding at a given point on the fan decreases as water moves down fan. This assumption acknowledges the fact that the downslope widening of the fan surface provides a greater area over which a channel of a given width may occur. For flood insurance purposes this produces ever-widening "probability zones" within which a channel of given geometry and discharge could be randomly located. These zones also exhibit decreasing values of depth and velocity in the downfan direction.

Edwards and Thielmann suggest that the discharge, depth and velocity would remain relatively constant as the water is transported by a specific channel in a downfan direction. Accordingly, for engineering design purposes, they have opted to remove the statistical component from the FEMA method, under the justification that "By eliminating the statistical component from the Dawdy (FEMA) method, the resulting flow characteristics represent conditions on the cone resulting from the 100-year peak discharges as determined at the apex, rather than conditions that would occur at any given point on the cone from an event which has one percent probability of occurring annually at that point."

They suggest that failure to follow this approach could lead to the design of flood-proofing measures or development criteria (in downfan locations) that could not withstand the flows that might realistically occur.

The second revision made to the FEMA (Dawdy) procedure was to assume normal depth would be a more realistic scenario than critical depth (as assumed by Dawdy). This modification acknowledges the potential for supercritical flow on the steep fan slopes and produces a more severe velocity parameter for design purposes. Edwards and Thielmann justify this assumption on the basis that the development of a critical depth channel would not occur until some time into the runoff hydrograph. Accordingly, until critical depth conditions are established, supercritical flow will probably be the predominant regime. It should be noted that in the 1985 revision to the FEMA procedure, normal depth is assumed for the multiple channel region of the fan, but critical depth is still assumed for the single channel region on the upper portions of the fan.

Based on the stated assumptions, Edwards and Thielmann present revised equations for computing flood depths, widths and velocities on an alluvial fan. These equations are based on Manning's Equation with an assumption of a wide, rectangular channel. The derivation of these revised equations also incorporates

Dawdy's criteria that an alluvial channel will continue to widen until a decrease in depth results in a two hundred fold increase in width, i.e., dD/dW = -0.005. The final equations resulting from these modifications are listed as follows:

$$D = \left(\frac{Qn}{178.8S^{1/2}}\right)^{3/8} \dots\dots\dots\dots\dots\dots\dots (6.10)$$

$$W = \frac{17.16(Qn)^{3/8}}{S^{3/16}} \dots\dots\dots\dots\dots\dots\dots (6.11)$$

$$V = 0.41Q^{1/4}S^{3/8}n^{-3/4} \dots\dots\dots\dots\dots\dots\dots (6.12)$$

where D = depth of flow (ft)
W = width of channel (ft)
V = velocity of flow (fps)
Q = discharge (cfs)
S = channel slope (ft/ft)
n = Manning's roughness value

When these relationships were applied to the Cabazon study, depths of 1 to 3 feet, velocities of 10 to 25 feet per second, and widths of 100 to 500 feet were reported for 100-year peak discharge values ranging from 5000 cfs to 30,000 cfs, and slopes ranging from 2 percent to 18 percent. Support for the computed velocities is reportedly provided by indirect field measurements (by the USGS) of flooding on alluvial fans. These measurements yield velocities in the 15 to 25 fps range. Application of the FEMA procedure to the same fans produced slightly lower velocities and deeper flow depths.

It is interesting to note that the flood hazard boundaries developed by the consultant for the Cabazon study were based on topographic constraints identified from topographic maps, aerial photographs, and historic flood data. These boundaries were not based on the channel widths computed with Equation 6.11. This was done to acknowledge the potential for flooding to occur at any point on a given contour of an alluvial fan.

Criteria for development standards for the community was based on established flood hazard boundaries and hydraulic calculations using Equations 6.10, 6.11, and 6.12. Scour depths were determined as a function of velocity, using Equation 6.12 and a scour depth/velocity relationship published by the Los Angeles Flood Control District.

Typical development standards that resulted from the study include requirements for: 1) slope protection to prevent damage from scour and erosion; 2) building pads to be elevated to a height above ground equal to the sum of the depth of flow plus the velocity head; and 3) limitations on minimum lot sizes and permissible housing densities. This third standard was established to insure that sufficient clear, unobstructed areas would be available to convey flood waters through a fully developed community.

For the Cabazon study, the consultant established permissible housing densities on the basis of the ratio of the computed channel width to the available flooding width. Minimum lot widths were found to range from 1/3 to 1/2 acre for single family residential use. Calculations also indicated that 30 to 35 percent of the lot width, in the direction of flow, must remain unobstructed.

6.3 Federal Insurance Administration, 1980 Experimental Procedure

Prior to publication of the FEMA/Dawdy procedure, described in Section 6.1 of this report, the Federal Insurance Administration (FIA) had experimented with a special flood insurance zone designated as "AF" (for alluvial fan). The mechanics of this procedure were based on unpublished work undertaken by Lare and Esyter of the Albuquerque District of the Corps of Engineers. A discussion of this procedure, presented in the following paragraphs, is based on an article by Magura and Wood (1980).

Description of Methodology

One of the most notable differences between this procedure and the FEMA/Dawdy procedure is the absence of a statistical parameter that reduces the probability of flooding in the downfan direction. As the reader will recall from Section 6.1, the FEMA/Dawdy procedure assumes that as the fan width increases (in the downfan direction), the probability of flooding along a given contour decreases because of the wider area available for a random channel location.

The FIA procedure places considerable emphasis on dividing the fan into separate reaches that exhibit similar flow characteristics. For example, possible reach limits are identified as: 1) the fan apex; 2) intersection points with main valley and canyon sides; 3) points of substantial change from an entrenched channel to a braided channel; 4) a change in overbank encroachments (structures); and 5) points of substantial change in gradient. Adherence to this recommendation will insure that each reach has relatively constant channel geometry and flow characteristics.

In conducting the hydraulic analysis of the fan, the FIA procedure utilizes two of the same assumptions contained in the FEMA/Dawdy method; i.e., 1) critical flow will be the dominant regime on the fan surface; and 2) channel geometry will stabilize when a reduction in flow depth produces a two-hundred fold increase in flow width.

The critical depth assumption is used to develop a set of curves relating overbank flow depth to a total flow path width. This is accomplished through the following steps:

1. Field inspections are conducted on the fan to determine the most representative channel geometry for the different reaches of the fan. For example, a rectangular cross-section (30-feet wide and 5-feet deep) was found by Lare and Eyster to be most representative for a site that was studied in New Mexico.

2. Using the representative channel geometry determined from Step 1, a water surface profile model (such as HEC-2) is used to develop hydraulic data for a range of discharge values and total flow widths. The total flow width includes both the incised channel bottomwidth and the overbank width. When using this procedure, the bottomwidth for a given channel is held constant and the overbank widths are varied. Using a critical depth assumption, the model is then run for these different combinations of discharge and total flow width. The model results will produce depths of flow and velocity data for the different elements of the cross-section.

Figures 6.1 and 6.2 represent typical depth-width curves that will result from applying the procedure described in Steps 1 and 2. These figures, which were adapted from the Magura/Wood article, also identify the cross-section variables that are used in the analysis. Figure 6.2 represents a sheetflow condition that would be typical of areas on a fan where there are no well-entrenched or defined channels.

Figure 6.1 Critical Depth vs Flow Path Width
Incised Channel With 30-Foot Bottomwidth

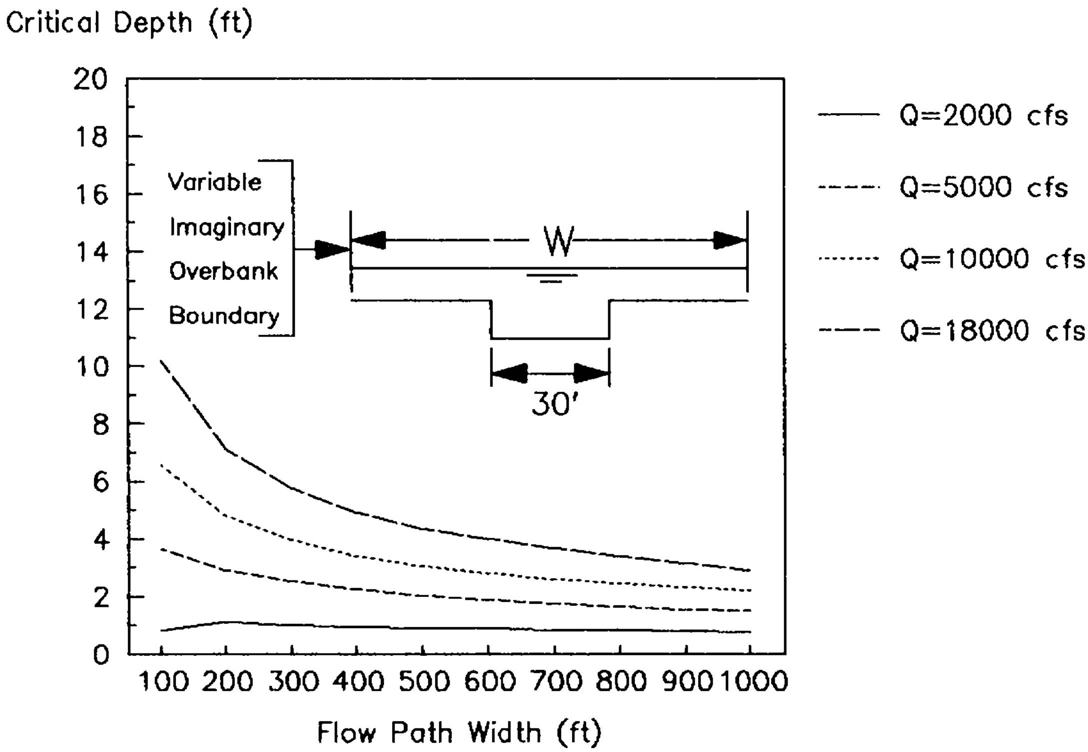
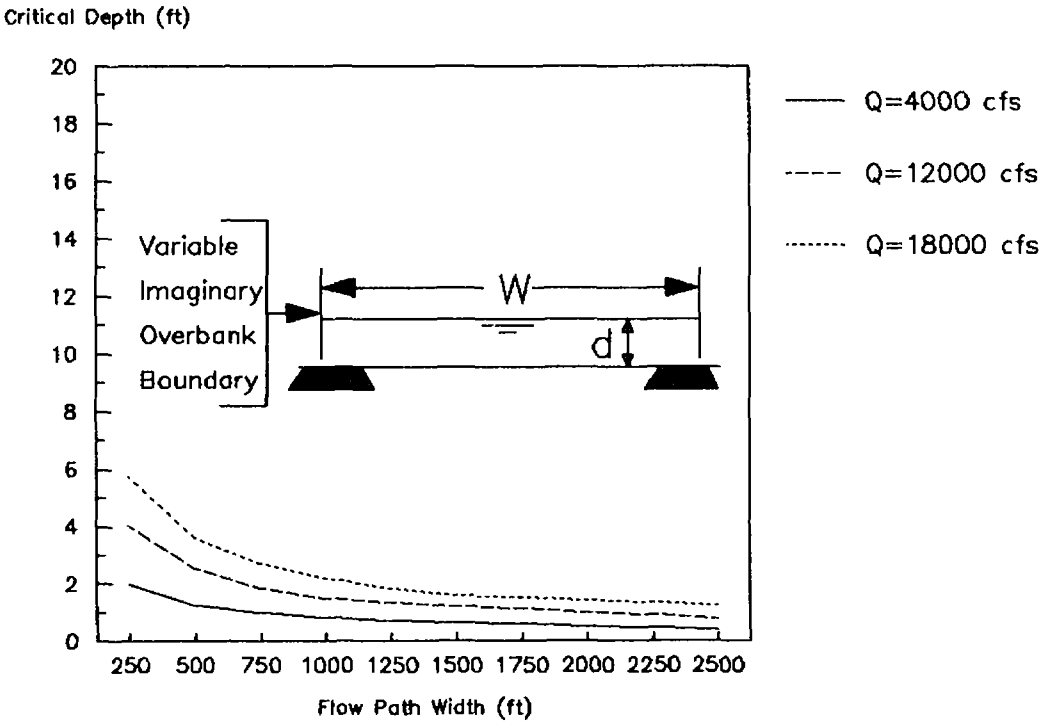


Figure 6.2 Critical Depth vs Flow Path Width
Overland Flow Conditions (no incised channel)



In concert with the previous emphasis on dividing the fan into separate reaches, each of which exhibits similar characteristics, the FIA procedure provides the following guidelines on how the different reaches might be analyzed:

1. ***Areas within the canyon, or areas on the fan surface where a deeply entrenched channel exists*** can be investigated with conventional procedures such as HEC-2. Caution should be exercised, however, to

insure that the channel has sufficient conveyance and stability to preclude the possibility of an
avulsion.

2. *Areas on an alluvial fan protected by structural works* (channels, diversion structures, debris basins, etc.) should be analyzed with a very critical evaluation of the performance capability of such structures. Issues such as adequate scour depths, sediment transport capacity, bank erosion, channel freeboard, etc. should be closely scrutinized.

3. *Majority of areas where natural fan processes, such as trenching, lateral migration of channels, and sediment deposition are free to take place,* should be analyzed under the two following categories:

a. *Unentrenched Fans* – A critical depth analysis for a shallow sheetflow condition (see Figure 6.2) is employed in this situation. The depth of flow to be used in this area is based on the previously cited assumption that lateral channel widening will terminate when a reduction in depth results in a two hundred fold increase in flow width. Using a chart similar to Figure 6.2, ratios of dD/dW can be computed for a given discharge until a ratio of 0.005 is found. The depth and flow velocity associated with this depth–width combination would then be considered representative for this reach of the fan. It should be noted that computed detph–velocity parameters are applied to <u>all</u> areas of the fan within this reach. This is based on the logical assumption that this is a random flow pattern that could, at some time, occur at any point across this reach of the fan.

b. *Entrenched Fans* – This condition is recommended for "those cases where an unbroken flow path exists which conveys up-canyon flow down-fan to a point where sediment deposition takes place." Straight, meandering and braided channels are included under this condition. Based on field data and/or topographic maps, a typical cross-section is developed for this reach. A depth-width relationship is developed, similar to that illustrated in Figure 6.1, and a flood depth (for the selected discharge) is determined in accordance with the $dD/dW = -0.005$ criteria. As previously discussed for the unentrenched fan condition, the computed depth and associated velocity parameters are assumed to apply at any point across the fan contained within this reach. Whenever, a noticeable change in channel geometry or slope is encountered, a new reach should be established, new depth-width curves developed, and new depth-velocity characteristics determined.

Comments on Methodology

Application of the FIA procedure allows the engineer to address both natural topographic and man-made features on an alluvial fan. The procedure emphasizes the importance of observing and measuring actual topographic features and provides a relatively simple basis for developing hydraulic data that could be used beyond the establishment of special flood hazard areas. Combined with bed-material samples, the hydraulic parameters developed from this procedure could also be used in sediment transport and scour calculations.

6.4 Soil Conservation Service Procedure

Under Public Law 566 (Watershed Protection and Flood Prevention Act), the Soil Conversation Service (SCS) is authorized to investigate the need for, and, if economically justified, design flood control projects at the request of local project sponsors. Several P.L. 566 projects in Arizona have required a flood damage analysis of alluvial fan environments in order to develop the benefit:cost ratio which determines the economic feasibility of a given project. In order to import some degree of consistency and standardization to alluvial fan damage analyses, James Malone (Hydraulic Engineer, SCS) developed a computer program to both analyze the hydraulics of fan flooding and to quantify the financial damage that would be expected to result from such flooding.

Unfortunately, this methodology was developed over 18 years ago and apparently has not been widely used. Mr. Malone no longer works for SCS, and the Phoenix SCS office was unable to locate complete documentation on the procedure. However, a brief outline (Malone 1971) of the methodology was available from SCS and provided enough data to generate a description of the basic assumptions used in the procedure. Accordingly, although the following discussion is not as complete and detailed as would be preferred, it does provide the reader with some basic ideas on yet another technical approach to analyzing alluvial fan flooding.

Description of Methodology

The SCS procedure focuses on the lateral (overbank) flooding that would occur on an alluvial fan in response to flows exceeding the bankfull capacity of an incised channel. Basic input parameters include a runoff.hydrograph at the fan apex and a typical cross-section for the channel reach that extends downstream from the fan apex.

Based on the limited documentation available to the author, it appears that the procedure is based on the hydraulic capacity of a single cross-section that is considered representative of the entire channel length. The procedure does not incorporate any continuous water surface profile calculations that would allow differentiation in bankfull capacity from the apex to the toe of the fan.

In essence, the procedure consists of routing the apex hydrograph (at selected time intervals) through this typical channel section to determine at what point in the hydrograph the bankfull channel capacity will be exceeded. The user has the option of selecting either one or both sides of the channel as overflow paths. Once the program determines that the channel capacity is exceeded, hydraulic calculations are performed to determine the velocity, depth, and volume of water that will spread laterally from the channel bank during the current time interval. The program includes controls to maintain flow continuity (i.e., overbank flow plus remaining channel flow does not differ from total available hydrograph flow for the current time interval) and computes infiltration losses for the laterally flowing water that escapes from the defined channel. Infiltration losses are also considered in maintaining continuity with the total hydrograph runoff volume.

Based on the limited text that was published in the 1971 outline, and the author's interpretation of the partial computer code that accompanied this outline, the overbank flooding calculations appear to proceed as follows:

1. Read apex hydrograph and determine discharge for current time.

2. Compare discharge from Step 1 to bankfull channel capacity to determine if overflow potential exists.

3. If Step 2 indicates overflow potential, compute overflow hydraulics; otherwise retrieve next set of hydrograph coordinates (Step 1).

4. The depth, velocity, and rate of overbank flow are computed through a trial and error procedure that is initiated by sequentially stepping through a range of <u>overbank</u> flow depths, until a depth value is found which will produce total flow continuity between the main channel, the overbank, and the hydrograph discharge for the current time. This set of calculations is predicated on the assumption that critical flow conditions will occur as water spills from the channel into the overbank. The calculation sequence is as follows:

   a. Using the assumed overbank depth, compute the overbank flow velocity as critical velocity, i.e., $V = \sqrt{gh}$.

   b. Using a previously computed main channel velocity, and the value of the current time interval, compute the length (in the main channel direction) along which overbank flow may occur. (Note: If the user has indicated that overflow may occur along both sides of the channel, this length is multiplied by two.)

   c. Using Q= AV, the total overbank flow is computed as the product of the assumed depth times the length (Step 4.b) times the velocity (Step 4.a)

5. If the discharge is Step 4.c is less than the overflow discharge from Step 2, a new overbank flow depth is assumed and Step 4 is repeated. The first depth value that produces an overbank flow equal to or greater than that from Step 2 is used as the most representative depth for the current time interval. The program increases overbank depth values in 0.005 foot increments.

6. The ultimate overbank flow depth produced by Step 5 is used to generate the lateral flow distance and area of inundation that will occur during a user selected overbank time interval. As discussed previously, the selected overbank depth is used to compute critical velocity, which is then multiplied times the selected time interval (0.02 hours was used in the program) to determine the lateral flow distance for the current <u>overbank</u> time interval. This lateral distance is multiplied by the previously computed downslope, main channel length (Step 4.b), for the current <u>hydrograph</u> time interval, in order to compute the surface area of overbank inundation.

7. For the second and successive lateral flow time increments, a velocity adjustment is made using Manning's Equation. The hydraulic radius is assumed equal to the depth of a unit-width flow-strip and the energy slope is assumed equal the difference between succesive overbank flow depths divided by the flow length for the previous overbank time interval. A Manning's roughness value is input by the user.

   This "friction velocity" is subtracted from the critical velocity associated with the current overbank depth value to derive an adjusted lateral velocity which is used to compute a lateral flow distance for the next overbank time interval. This adjusted velocity is also used to compute a new critical depth, which is then assumed to represent the overbank flow depth for the next block of laterally propagating flow. This procedure results in an ever-decreasing lateral velocity and associated lateral flow depth. The lateral flow calculations are allowed to propagate out from the channel bank until the overbank flow depth is less than 0.04 feet. Procedures are included to keep track of cumulative surface area inundation and flow volumes.

As indicated previously, infiltration losses are included in the lateral flow calculations and are used, in addition to the adjusted velocity calculation, to reduce the depth of the widening overbank flow.

Comments on Methodology

Again, due to lack of sufficient documentation, there was no information available to explain how succeeding intervals of the apex hydrograph were manipulated to adjust overbank flow depths for the increasing channel discharges (beyond the first discharge interval that exceeds bankfull capacity) that will cause an increasing amount of water to flow over the channel banks.

The available documentation also failed to explain the mechanics of routing the overbank flood wave downstream. The 1971 report states that the "downslope velocity is the same as channel velocity and remains constant." This would appear to be a questionable assumption, since the flow concentrated in the main channel will undoubtedly flow much faster than the shallow sheetflow associated with the overbank. The report also indicates that the area flooded by the overbank flood wave diminishes as the wave propagates downfan. However, again there was no documentation to explain the technical basis for the attenuation of the wave.

Although the foregoing discussion is not a complete description of the SCS procedure, it provides insight into the general concept that is being employed. In summary, this concept is based on identifying the bankfull capacity of an incised channel and then determining the depth, velocity, and discharge of overbank flow when the channel capacity is exceeded by runoff emanating from the apex of an alluvial fan.

Without having an opportunity to review the results of a case history where the procedure has been applied, it is difficult to critique the realism of the results that the procedure would produce. An obvious limitation of the procedure is that is requires the existence of a stable (non-erodible) channel cross-section and confines the analysis to this single cross-section location.

Such an approach may be applicable to a project that requires an analysis of a stabilized, man-made channel of constant cross-section. Application of the procedure to such a project may provide beneficial data on overbank flooding characteristics. However, utilization of the procedure for a natural channel reach of variable cross-sectional geometry may generate substantially erroneous results.

A unique feature of the program is the capability to convert the overbank hydraulic data into a financial summary of predicted flood damages. Obviously, this requires the user to develop some type of rating curve for the project area that will relate depth and/or velocity of overbank flow to dollars of flood damage.

Discussions with personnel from the SCS office in Phoenix indicate that the only known application of this procedure in Arizona has been for the economic analysis of the Guadalupe Flood Retarding Structure near Interstate 10 and Baseline Road, south of Phoenix.

6.5 Simulation Of Alluvial Fan Deposition By A Random Walk Model

Although the procedure described in this section may not have a substantial amount of practical value to engineers engaged in the design of highways, urban development, and flood control improvements on alluvial fans, it does provide a very unique and interesting approach to the mathematical construction of an alluvial fan.

This methodology, developed by Price (1974), consists of a 3-dimensional computer model (*Alfan*) which incorporates mathematical algorithms that quantify the physical parameters responsible for the creation of an alluvial fan. The primary objective of this undertaking was to obtain a better understanding of the "hydrogeologic fabric" of fans. Such research could provide benefits relative to estimation of aquifer parameters, interpretation of aquifer tests, accurate correlations of borehole data, and a better understanding of the types of data collection needed to adequately define the alluvial fan hydrogeologic system.

Price has essentially taken taken the observations and theories presented in Section 2.2 (The Alluvial Fan) of this report and converted them into mathematical expressions that can be used to quantify both the form and stratigraphy of a fan. The resulting model quantifies and integrates the following processes to simulate fan development:

1. Tectonic activity
   a. timing
   b. magnitude

2. Drainage basin processes
   a. accumulation of erodible material in the mountain source area.
   b. degradation of mountain stream in response to mountain uplift.

3. Alluvial fan processes
   a. uses 3-dimensional node network to govern the probability of direction of flow on the fan surface.
   b. differentiates between water flows and debris flows.
   c. acknowledges physical barriers that might restrict fan growth or development.
   d. simulates branching of flows.
   e. simulates the random distribution of flow events with respect to both time and magnitude.
   f. simulates fan entrenchment when conditions favor such a phenomenon.

The following paragraphs present a brief discussion of the techniques employed by Price in developing this model.

Tectonic Activity

As the reader will recall from Section 2.2.4, Bull (1967) developed an expression (Equation 2.7) that requires the rate of change of tectonic uplift of the mountain mass to be equal to or greater than the sum of the rate of change of channel downcutting in the mountain plus the rate of change of fan deposition at the mountain front. Accordingly, tectonic activity is incorporated in the model as a function of vertical movement along a fault line assumed to be located at the mountain front. Relative uplift along the fault is then assumed to be a function of earthquake activity. Price justifies these assumptions on the fact that topographic development in the Basin and Range province is frequently the result of normal faulting and is closely associated with earthquakes.

Earthquake activity is simulated in the model by using the Poisson probability law to predict the interoccurrence times of earthquakes, and a set of regression equations relating the magnitude of an earthquake to both the vertical displacement and length of movement along the fault. The timing and magnitude distributions used to model the tectonic activity are assumed to be independent of each other.

Two sets of regression equations were developed to apply to earthquakes with a magnitude of less than 6, and for events with a magnitude of 6 or greater. For example, the vertical movement along a fault, as a result of an earthquake magnitude of 7 (Richter scale), is computed with the following equation:

$$H_f = \frac{10^{(M_e - 5.02)/1.04}}{30.48} \qquad (6.13)$$

where H_f = maximum vertical displacement along the fault (feet)

M_e = earthquake magnitude (Richter scale)

A random value of the earthquake magnitude is generated from the equation:

$$M' = \left(-\frac{1}{\beta}\right)\ln(1 - R_u) + M_o \qquad (6.14)$$

where M' = random value of earthquake magnitude

β = $b/\log_{10} e$

where b is the parameter in the formula of Gutenberg and Richter (1954)

R_u = a random value from a uniform distribution over the open interval (0, 1)

M_o = minimum magnitude of earthquake events to be considered (events with a magnitude less than 4 are ignored as being insignificant from an engineering perspective)

Equations 6.13 and 6.14 are only a sample of the numerous algorithms used to model the occurrence of tectonic activity. The complete set of equation forms computer subroutine *Uplift*.

Drainage Basin Processes

The development of alluvial fans is very dependent upon the decomposition, erodibility and transport of material from the mountain source area to the fan surface. *Alfan* includes a subroutine (*Basoil*) which computes the thickness of a weathered soil layer as a function of both time and the rate of increase of the weathered thickness of the material. The relationship employed by *Basoil* is presented as follows:

$$y_s = m_s(1 - \exp(-\eta t_s)) \qquad (6.15)$$

where y_s = thickness of the weathered layer (feet)

m_s = maximum thickness of weathered layer (feet)

t_s = time increment in years

and $\eta = \epsilon c / m_s$

where ϵ = dimensionless constant, equal in numerical value to m_s

c = rate of soil accumulation in feet per year

The thickness of this weathered soil layer (at the time of a simulated flow event) becomes an important factor in determining if a debris flow will occur (this will be discussed in subsequent paragraphs). Unfortunately, Price does not provide a clear explanation of the algorithm that is used to transport the weathered material from the source area to the fan.

The process of channel degradation within the mountain source area is modeled under the assumption that erosion will lower the stream channel in the basin at the point where the mountain boundary fault crosses the stream channel. The following relationship is employed for this purpose:

$$h = H_o \exp(-k_c t_i) \ldots\ldots (6.16)$$

where h = elevation of the stream bed in feet above the base level at time t_i

H_o = elevation of the stream bed in feet above the base level immediately following an uplift at time t_o

k_c = average rate of decline of the rock channel (feet/year) near the fault crossing

Alluvial Fan Process

The movement of water and debris flows across the alluvial fan surface is controlled by a network of 3-dimensional nodes that are used to compute the probability that flow will move from a central node to an adjacent node (the term ***one-step transitional probabilities*** is used by Price). These probabilities are computed by having the computer first subtract the elevation of the central node from the elevation of each adjacent node. If this elevation difference is positive for any node, the probability of movement to such a node is considered to be zero. If the elevation difference is zero or a negative value, there is a possibility that flow could move in the direction of such a node and, therefore, the gradient to each of those nodes is computed. An assumption is then made that the probability of flow to each node is proportional to the computed gradient between the central node and each adjacent node. Specifically, this probability is computed by the following equation:

$$P_s = 0.25 + 0.75S \text{..................}(6.17)$$

where P_s = probability of movement

S = gradient (slope) from the central node to an adjacent node

At this point the model makes an important distinction between water flows and debris flows. For water flows, the gradient is computed from the base of flow at the central node to the adjacent nodes, while the gradient for debris flows is computed from the top of the debris flow at the central node. Accordingly, this provides debris flows with a capability to move up a land slope, as long as the land surface elevation is not higher than the top of the debris flow. The presence of a debris flow or water flow is determined as a function of the thickness of the weathered soil layer in the mountain source area at the time a specific flow event occurs.

The flow of water and deposition of sediment onto a fan surface will be controlled by certain physical boundary conditions. These boundaries might typically include the mountain front and periphery of the area allotted for fan development. When the random member generator triggers a potential flow movement into such a boundary, the flow will not move.

Price also discusses the requirement for a flow event in the model to reach an "absorbing state". An absorbing state is defined as one in which the one-step transitional probability equals 1. Once an absorbing state is reached, the flow event ends. The user has an option of defining absorbing barriers along the perimeter of the grid network. It should also be noted that Price indicates an absorbing state can also be reached under the law of conservation of mass. This requires that the volume of deposited sediment must equal the total sediment load transported during the flow event.

Alfan includes a procedure to simulate the branching or braiding of flow patterns that typically occur on an alluvial fan. Branching occurs in the model when flow becomes trapped by either of the two following constraints:

1. no flow may cross or intersect itself.
2. no <u>water</u> flow may occur in the direction of a positive gradient (uphill)

When either of these conditions are reached, *Alfan* retraces the course of flow and searches for another node of possible movement. When one is found, a new flow path is initiated.

A unique case may occur in which no movement can take place in any direction along the previous flow path. This would simulate a blocked channel or a depression in the fan surface. When this occurs, the channel or depression will be filled with water and/or sediment to the elevation of the lowest outlet of the depression, where a new flow path will than be computed.

As for tectonic uplift events, the time distribution of flow events is also determined by application of the Poisson probability law. The ultimate expression developed to predict the timing of flow events is:

$$t' = \left(-\frac{1}{\lambda_f}\right)\ln(1 - R_u) \ldots\ldots(6.18)$$

where t' = years

λ_f = mean rate of occurrence of flow events in flows per year (must be initially specified by the user)

R_u = random value from a uniform distribution over the interval $0 < R_u < 1$

The same general form of algorithm is used to compute the random occurrence of an uplift event. The timing of flow events and uplift events are independent of each other. The model computes a random time for a flow event and a random time for an uplift event. The two times (flow event vs. uplift event) are then compared and the model selects the earlier time to determine what event to pursue. If a flow is selected, subroutine *Storm* is called, if a tectonic event is selected, subroutine *Uplift* is selected.

The magnitude of flow events is derived from an exponential distribution of flow magnitudes. After some mathematical manipulation, the final algorithm for computing the flow magnitude is presented as:

$$y'_f = -\gamma \ln(1 - R_u) \qquad (6.19)$$

where y'_f = random value of peak flow rate (cfs)

γ = mean peak flow rate (cfs)

R_u = random value from a uniform distribution over the interval $0 < R_u < 1$

The magnitude of a flow event is completely independent of the timing of such events.

Although Price does not elaborate on the details involved in computing the magnitude of a flow event, it would appear that the user must develop some type of hydrologic data for the source area in order to provide a value for γ.

As indicated previously *Alfan* has the capability of generating both debris flow deposits and water flow deposits. The model is configured to trigger a debris flow when a storm event occurs at a time in which the thickness of weathered material in the source area equals or exceeds the value of a parameter designated y_c. If the thickness of the weathered material is less than y_c, a water flow will result. The user has the option of varying the value of y_c to reflect the erodibility (ability to be transported from the mountain slope to the mountain stream) of the source basin material. A low value of y_c would indicate a source basin that is composed of easily erodible weathered material.

The coefficient *c* in Equation 6.15 can also be varied to determine the rate of weathering (decomposition) of the soil layer. Smaller values of *c* will cause a longer period of time to ensue before a sufficient thickness of weathered soil (y_s) is generated to cause a debris flow ($y_s \geq y_c$).

During a debris flow, the volume of material that is transported from the source area onto the fan is simply the product of the thickness of the weathered material times the erodible area of the source basin. Price does not provide details on how sediment volumes are computed for water flows. It is assumed that a similar scheme would be used involving the thickness of the weathered material and the size of the source area. Immediately after a storm event occurs, Equation 6.15 is used to begin regeneration of a new weathered soil layer.

The actual shape and deposition of material on the fan surface is controlled by the volume of sediment transported from the source area and two user-designated variables, *Bthick* and *Wthick*, which identify the mean thickness of debris flow and water flow deposits, respectively. Although other options are available in the model, both debris flow and water flow deposits are generally assumed to be tapered in the direction of flow from a maximum of two times *Bthick* (or *Wthick*, as appropriate), at the point of initial deposition, to zero at the end of the flow.

A final feature of *Alfan* is its capability to simulate temporary entrenchment of the fan through a process termed "negative deposition". This process will occur when either of the following conditions exist:

1. when the fan material just below the point where the main channel crosses the fault lies at a higher elevation than that of the stream channel emerging from the mountain area just above (upstream of) the fault, or
2. a flow event occurs when there is very little erodible sediment in the source basin, causing the mountain channel to flow onto the fan surface with an underload of sediment.

The course of erosion that results from either of these conditions is a random walk, which is computed by the transitional probability concept discussed previously.

As originally developed, the output from this model provides data relative to the stratigraphy and topography of the fan. The original paper by Price provides illustrations showing how this output data can be used to generate both topographic and geologic maps of an alluvial fan. Illustrations were provided where the data was used to develop geologic cross-sections of the fan, both perpendicular and parallel to the mountain front.

Although this model is oriented towards the geologic and hydrogeologic investigations of alluvial fans, it provides an excellent example of how the complex, theoretical processes at work on a fan can be transformed into mathematical relationships that can be used to explore the impact and sensitivity of certain variables that control alluvial fan formation. The results of the experiments conducted by Price indicates that the model creates a landform that has the geologic characteristics and topography of an alluvial fan.

6.6 Continuous Hydrologic Simulation Model

Urbanization of alluvial fans will undoubtedly create a significant risk for property damage if such development is not properly planned. Recognizing that conventional riverine flood hazard delineation techniques are not suited for application to alluvial fans, James, Pitcher, Heefner, Hall, Paxman, and Weston (1986) describe the development of a methodology which attempts to address the unique hydrologic, hydraulic, geologic, and sediment transport processes that are responsible for damage to urbanized areas located on alluvial fans.

This methodology, which is called a *continuous hydrologic simulation model,* actually consists of five sub-models which have been linked together in order to continuously track the erosion, flow, and deposition of the water/sediment mixture from a mountain source area onto an urbanized fan environment. The five sub-models are identified as follows:

1. Runoff and Sediment Yield Model
2. Landslide Prediction Model
3. Steep Channel Routing Model
4. Sediment Deposition and Culvert Blockage Model
5. Multiple Path Flood Routing Model

Unfortunately, the 1986 publication that describes this procedure is very brief and does not provide specific details on how the algorithms in the different sub-models are linked together. However, the text does provide sufficient information on the general methodology that is employed by each sub-model. Accordingly, the model is summarized in the following paragraphs in order to provide the reader with yet another interesting approach to the mathematical simulation and analysis of alluvial fan flooding characteristics.

Runoff and Sediment Yield Model

The runoff portion of this sub-model uses a water-balance accounting procedure to track the total amount of water stored in the snowpack, on the ground surface, in the phreatic zone, in any perched water table, and within bedrock. Water is allowed to flow from and through these different zones to ultimately reach the stream channel. Temperature and solar radiation are used to estimate evapotranspiration and to distinguish rain from snow.

Other than a statement that "Mountain storage gage data were used to estimate the storm precipitation increase with elevation", no information was provided in the article relative to the options for inputting frequency, duration, distribution, and amount of rainfall to the model. There was also no discussion provided relative to the methodology that was used to perform overland flow runoff calculations. However, this sub-model is described as being developed from the Stanford (Kentucky version) Watershed Model. Accordingly, it is presumed that the hydrologic calculation scheme in the Stanford model forms the basis for runoff calculations in this sub-model.

Sediment yields were computed with the Modified Universal Soil Loss Equation (MUSLE). Both the peak discharge and total runoff volume (computed in the runoff segment of this sub-model) are used by MUSLE (along with four other parameters) in computing the sediment yield from the watershed.

Landslide Prediction Model

Factors related to soil classification, depth, permeability, moisture content, cohesion, internal friction angles, ground cover, slope, and elevation are used by this sub-model to predict the timing, location, and volumes of landslides. For the example discussed in the published article, calibration mechanisms were available to match data from observed landslides.

Application of this model to the example watershed utilized a grid network consisting of 263 grid cells over a 2.54 square mile area, to identify the soil parameters required for input to this sub-model. There was no information provided to indicate how the landslide data was integrated with the four other sub-models. It may be that the output from the ***Landslide Prediction Model*** is an end product in itself and is merely used to predict zones subject to a high risk of landslide activity.

Steep Channel Routing Model

This sub-model uses kinematic routing to translate runoff hydrographs through the network of steep mountain channels. The depths and velocities of flow resulting from the channel routing operation are used as input data to sediment transport equations which were in turn used for sediment routing operations. Sediment transport calculations were based on equations developed by Smart (1984) for channels with slopes ranging from 4% to 20% and median grain size diameters greater than 0.4 mm.

No details were provided on the actual sediment routing operations used in this sub-model; only a statement is made indicating that a sediment balance is applied to each channel reach to model aggradation and degradation.

This sub-model also contains the capability to simulate debris flow blockage of channels and the subsequent filling, overtopping, and erosion (collapse) of these temporary dams.

Sediment Deposition and Culvert Blockage Model

Movement of the sediment laden water across the fan surface will frequently encounter culvert crossings of roads. These culverts are often prone to complete or partial blockage due sediment deposits. The Sediment Deposition and Culvert Blockage Model simulates this potential for culvert blockage. This sub-model description also infers that a weir flow calculation is performed to represent the overflow that would occur across the road surface when water ponds above the headwall (or roadway embankment) elevation at the culvert inlet.

Sediment transport calculations utilize the Meyer-Peter, Muller (MPM) bed-load transport equation, with an assumption of inlet control at the culvert entrance. Although specific details are not provided, the article indicates that a friction slope is calculated for the water movement through the inlet pool and is used to generate the hydraulic data needed for the MPM calculations.

The discussion of this sub-model also implies, although specifics are not given, that sediment is routed through culverts and transported to downstream locations for additional culvert routings.

Multiple Path Flood Routing Model

This subroutine is used to trace flow paths through the street systems that would exist on an urbanized fan. Provisions are included in this sub-model to combine local runoff into the routed hydrographs and to acknowledge grade changes and infiltration loses as flows exceed the street capacity and pass over permeable soils of adjacent residential lots.

Due to the propensity for critical flow conditions to occur on the relatively steep street slopes that would be typical of alluvial fan developments, kinematic routing procedures are employed. Flow splits at street intersections are based on energy and momentum relationships. The hydraulic geometry of streets is based on surveyed cross-sections. This cross-sectional geometry can be combined with the peak discharge data from the kinematic routing calculations to determine depths and velocities of flow, as well as areas of inundation along the streets.

Although complete technical details of this methodology are not provided in the foregoing summary, the general approach should alert the reader to the fact that analytical tools are available that may have useful application to specific problems encountered by the engineer working in an alluvial fan environment. A review of such methodologies should also serve as a stimulus to those innovative engineers who may wish to develop an analytical technique to solve a specific problem encountered in the design of civil works projects on a fan. As both this and the preceding technical discussions indicate, a sound understanding of alluvial fan processes can serve as the basis for developing mathematical relationships that can prove invaluable in quantifying the impacts of both hydraulic and sediment transport processes on alluvial fans.

6.7 Corps of Engineers Design Standards for Alluvial Fans

Under contract to FEMA, the Los Angeles District Corps of Engineers (COE) has published a report entitled: "*Engineering Standards For Flood Protection of Single Lot Developments On Alluvial Fans*" (undated). The author was furnished a "draft" copy of this report by the COE. Although the report is undated, references in the report indicate it was prepared in 1985 or later.

Description of Methodology

Although the introductory chapters of the COE report present a brief discussion on alluvial fan characteristics and management practices, the majority of the report is devoted to the presentation of quantitative relationships that can be used by a professional engineer in designing elevated floodproofing measures for single lot developments on alluvial fans. Considerable emphasis is placed on the use of sound engineering judgement in applying the design aids presented in the report. The COE relates the design of floodproofing measures on alluvial fans to the three general hydraulic zones or flow patterns described by Anderson-Nichols (1981) : 1) channelized zone; 2) braided zone; and 3) sheet-flow zone. A detailed discussion of these zones is presented in Section 7 of this report.

Basically, the COE concludes that development can be allowed in the channelized zones if it can be shown that the channel capacity is sufficient to contain the flow from the design event (typically a 100-year flood). Unless the channel is incised into bedrock, restrictions should preclude any development near the channel banks; this provides a measure of safety against lateral bank erosion. Obviously, no development of any kind should be allowed in the channel area.

Flow in the braided zone is characterized by multiple channel patterns which can cause rapid shifts in the flow alignment. This is also a zone with a high potential for sediment deposition. The COE recommends that any structures built in this zone be elevated on armored fill or by the use of posts (piles).

Due to the flatter surface slope, the <u>sheet-flow zone</u> is typically associated with lower-velocities (3 to 5 fps) which do not transport large quantities of sediment. The COE recommends elevated structures in this zone as well as the use of walls.

Given the absence of a rigorous methodology to quantify the boundaries of these three zones, the COE recommends close examination of topographic maps and aerial photographs of a given project area. Certainly, extensive field investigations are also warranted. As a matter of interest, the reader will recall that the FEMA procedure (Section 6.1) utilizes an empirical relationship to determine the length of the single channel region on a fan. The single channel region is analogous to the channelized region referenced by the COE.

Prior to discussing the specific equations recommended by the COE for designing flood proofing measures, a review of their general design procedure is warranted. The COE suggests the following steps be followed as part of the design process:

1. Undertake an evaluation of the characteristics of the <u>entire</u> watershed. This would include the mountain source area as well as the fan surface.

2. Prepare a hydrology analysis to determine the peak discharge values associated with storms of up to at least the 100-year event. The COE notes that this data may already be available through various federal agencies or local regulatory agencies. The author would like to add that special attention should be given to the location on the fan at which the discharge values apply, i.e., apex, midfan, etc. Flood hydrographs can experience extreme attenuation as they pass through the braided and sheet-flow zones of a fan.

3. Examine any available historic data on flood behavior, flow direction bias, and any significant topographic features on the fan which might obstruct or deflect flow patterns.

4. Determine the potential (probability and magnitude) for debris flows. This will require a close examination of the mountain source area. Historic records would also be helpful.

5. Calculate the hydraulic parameters (depth and velocity) for the location at which the flood proofing measure will be designed. The equations used for these calculations are based on water flow, not debris flow.

6. Develop and evaluate alternative flood proofing designs for the site.

7. Evaluate the impact of any potential debris flows on the alternative designs. The COE suggests that debris flow effects can be accounted for by increasing the height of fill, streamlining the shape of the fill, or, in the case of posts, increasing the size and height of the posts.

8. Examine the impact that the proposed design will have on adjacent and downstream properties. If adverse impacts are created, a mitigation plan will be required.

9. If a Master Plan has been developed for the area (see Section 7), check to make sure the design alternatives are compatible with such a plan. The author would recommend that this step be accomplished <u>prior</u> to initiating work on the design alternatives (Step 6).

10. Evaluate the costs of the alternatives and select the most feasible design for submittal to the local regulatory agency.

In undertaking the design of single lot, elevated floodproofing measures, the COE recommends using the equation developed by Edwards and Thielmann (See Section 6.2) for computing depth and velocity (Equations 6.10 and 6.12 respectively). Very simply, these equations are used to compute the height of the fill (or posts) and the velocity to be used in bank erosion protection and scour calculations.

Due to the potential for significant amounts of debris in alluvial fan flows, the COE recommends that this phenomenon be considered by raising the height of the fill, increasing the thickness of the slope protection, or by increasing the height, embedment, and thickness of posts to account for impact forces of debris. The magnitude of these increases is left to the judgement of the professional engineer, who should make such decisions on the basis of watershed characteristics and location of the structure on the fan. The COE does, however, provide quantitative guidelines for computing the height of flood proofing, exclusive of debris flow impacts. The following equation is presented:

$$H = D + \frac{V^2}{2g} + X \geq 2.0 \quad \text{............(6.20)}$$

where H = height of floodproofing measure (feet)

D = depth of flow (feet), computed from Equation 6.10

V = velocity of flow (fps), computed from Equation 6.12

g = gravitational constant (32.2 ft/sec^2)

and $X = D_{1.5xQ\ Design} - D_{Q\ Design} \geq 0.5$ feet

where $D_{1.5xQ\ Design}$ = depth of flow (ft) that would occur if the design discharge were increased by 50%

$D_{Q\ Design}$ = depth of flow (ft) at design discharge (same as D above)

The velocity head is included in Equation 6.20 to address the potential for the flow to hit an obstruction and cause a conversion of kinetic energy (velocity) to potential energy (depth). The "X" term is a freeboard factor to provide a margin of safety for calculation uncertainties (a minimum freeboard dimension of 0.5 ft. is recommended). Equation 6.20 also requires a minimum total floodproofing height of 2 feet.

Due to the potential for high velocity flow on an alluvial fan, the occurrence of bank erosion and scour along the boundary of the fill must be investigated. In a similar vein, localized scour should also be analyzed for any posts that might be used to elevate a structure.

For elevated fill, the COE report addresses three types of bank protection: 1) rock riprap; 2) grouted rock; and 3) gabions. Of these three methods, rock riprap requires the most intensive technical analysis to establish the proper rock size and gradation.

rock riprap

The COE report presents an intermediate form of the Isbash method as the preferred approach to relating rock size to flow velocity on an alluvial fan. The recommended equation is published in the COE report as:

$$W_{50} = 12 \times 10^{-5} V^{6} \ldots\ldots\ldots\ldots\ldots (6.21)$$

where W_{50} = weight (lbs) of a spherical stone that has a diameter equal to the D_{50} rock size (ft) for which 50% of the graded riprap material is smaller

V = velocity of flow (fps), computed from Equation 6.12

The W_{50} values that are computed from Equation 6.21 are used to enter a table of stone gradations published in the COE report. A gradation is then chosen in which the minimum W_{50} is equal to or greater than the W_{50} computed with Equation 6.21.

Equation 6.21 is described as an intermediate form of the Isbash method because of a judgemental factor that was introduced by the COE to account for the turbulence level that is expected to exist on an alluvial fan. The COE report states:

"Flow on an alluvial fan represents a decelerating condition as slopes tend to decrease and the channel width increases in the downstream direction. According to Stephen T. Maynord, the vorticity generated in an expansion is intense and irregular and can resemble the turbulence downstream of an energy dissipater. The turbulence of low on an alluvial fan is greater than for tranquil flow, but not as turbulent as at the end of an energy dissipater. Therefore, an intermediate form of the Isbash equation is chosen for computing riprap rock sizes on alluvial fans."

The COE accounts for this turbulence variation by adjusting the "c" coefficient in the Isbash equation taken from the Corps of Engineers Hydraulic Design Criteria (1970). The published equation is:

$$V = c\left(2g\frac{(\gamma_s - \gamma_w)}{\gamma_w}\right)^{1/2} D_{50}^{1/2} \qquad (6.22)$$

where V = velocity (fps)

c = coefficient

g = gravitational constant

γ_s = specific weight of stone (lb/ft^3)

γ_w = specific weight of water (lb/ft^3)

D_{50} = stone diameter (ft) of the rock size for which 50% of the graded material is smaller

The value of c is published as 0.86 for high turbulence levels that might exist at the end of an energy dissipater in a stilling basin, and 1.20 for low turbulence levels that might be associated with river closures. Through mathematical substitution and manipulation, Equation 6.22 is ultimately transformed into Equation 6.21. When c is assumed to be 0.86 and 1.20, the coefficient in Equation 6.21 will be 18.03x10^{-5} and 2.44x10^{-5}, respectively. Based on Maynord's discussion of turbulence levels, the COE chose an intermediate coefficient of 12x10^{-5} to be used in Equation 6.21.

For those readers who might wish to investigate the influence of different rock specific gravities and side-slope angles, the COE report also publishes a form of the Isbash equation taken from the ASCE Manual No. 54, Sedimentation Engineering (1975):

$$W_{50} = \frac{4.1 \times 10^{-5} G_s V^6}{(G_s - 1)^3 \cos^3 \theta} \dots\dots\dots\dots\dots\dots (6.23)$$

where W_{50} & V are as defined for Equation 6.21

G_s = specific gravity of the stone

Θ = the angle the slope makes with the horizontal

Through sample calculations, the author has determined that Equation 6.23 will produce the same value for W_{50} as Equation 6.21, <u>if</u> the numerical coefficient in Equation 6.23 is changed from 4.1x10^{-5} to 14.5x10^{-5}. This calculation assumes G_s=2.65 and the side-slope is 2H:1V. Although not proven, it would seem that the use of this revised coefficient (14.5x10^{-5}) in Equation 6.23 would make it equivalent to Equation 6.21 for any realistic range of specific gravities and side-slope angles. This would provide the user with a more flexible equation if variations in specific gravity and side-slope were to be investigated. The use of this larger coefficient would provide a factor of safety of approximately 3.5 for the W_{50} values computed with the original coefficient in Equation 6.23.

grouted rock

If rock riprap of the required size and gradation is not readily available, the COE report suggests that grouted rock may be used as an alternative. Grouted rock can be installed with colored grout to enhance the aesthetic appearance of the product. It can also be covered with soil (18" minimum cover is recommended) and planted with shrubs or grass. For grass cover, a maximum slope of 3H:1V is recommended for ease of mowing.

The general design guidelines for grouted rock suggests 6 to 12 inch rock sizes placed in a layer approximately 12 inches thick. The rock layer is then grouted so that 50% of the interstitial voids are filled and about one-third to one-fourth of the stone diameters are left projecting beyond the grouted surface.

gabions

Gabions, which are wire-mesh baskets filled with stone and tied together to form a flexible mattress, can also be used if satisfactory rock sizes are not available for loose rock riprap. The typical thickness of these baskets ranges from 9 to 18 inches. This thickness is a function of flow velocity. Several gabion manufacturers publish design criteria for their products.

As indicated previously, the design of a bank protection measure for elevated fill must also address the scour potential along the boundary of the fill. The COE report recommends that toe-down dimensions for bank protection be based on data published by the Los Angeles County Flood Control District, with minor modifications by the COE. The recommended toe-down depths are reproduced in Table 6.1. It should also be noted that streamlining the shape of the fill would be an effective method of reducing the scour potential along the fill perimeter.

The use of posts or piles to elevate a structure above anticipated flood hazards is also subject to scour problems. Such structures create the same type of scour problem as is encountered in the design of bridge piers. The COE report suggests the use of the following equation developed by Shen and Neill (1964):

Table 6.1
Toe-Down Depths for Armored Fill on Alluvial Fan Residential Lots

Velocities (fps)	Toe-Down Depth (ft)
0-2	0
2-4	3
4-6	6
6-10	8
10-15	10
15-18	12.5
18-20	14

The data in this table is taken from "*Engineering Standards For Flood Protection Of Single Lot Developments On Alluvial Fans*", Table 1, page 24, U.S. Army Corps of Engineers. Toe-down depths are for straight reaches.

$$\frac{d_s}{d} = 2\left(\frac{b}{d}\right)^{0.65} F^{0.43} \qquad (6.24)$$

where d_s = depth of scour hole (feet)
d = upstream depth of flow (feet)
b = width of pier or post (feet)
F = upstream Froude number

This equation was developed for a group of circular cylinders. The COE recommends that answers obtained using Equation 6.24 be increased by a factor of 1.3 and then added to the general toe-dimensions listed in Table 6.1 to determine a total embedment depth for the post.

floodwalls

For the lower hazard areas on a fan (such as the sheet-flow area), freestanding walls may be considered as a protective measure for single lot developments. Recommended limitations on their use would be in areas where flow depths do not exceed 1 or 2 feet, and velocities are in the 3 to 5 fps range. They should not be considered in debris flow areas.

In designing this alternative, special consideration will have to be given to property access and the disposal of interior drainage.

costs

The cost of constructing flood proofing measures is obviously an important factor to consider in the decision to build a residence on an unprotected alluvial fan. Based on 1985 construction costs near the Rancho Mirage, California area, the COE report estimates that the cost to elevate a structure on piles could range from $9700 to $10,600; the cost for elevated fill protected by rock riprap could range from $13,400 to $130,000; and the cost of elevated fill with grouted rock could lie between $14,600 and $37,600. These cost differences are based on a typical residential structure subjected to a variable range of depth and velocity combinations.

Comments on Methodology

Table 6.1 lists toe-down depths as a function of velocity. The COE report does not indicate what type of bed-material (i.e., sand, gravel cobbles, etc.) this relationship was based on. Obviously the sediment particle size would influence the amount of scour potential at a given location. This table should be footnoted to indicate the applicable range of sediment sizes.

Only three types of bank protection were presented in the report (rock riprap, grouted rock, and gabions. In the dynamic and high velocity environment that exists on an alluvial fan, the author would suggest that caution be exercised in using any of these three products. Even though quantitative relationships are presented for sizing rock riprap, these equations are theoretical. The technical literature contains many different riprap design procedures, nearly all of which will produce different rock sizes for the same set of design conditions. Accordingly, in the absence of full scale tests on an alluvial fan subjected to a severe flood, it is difficult to predict which riprap design methodology would yield the most accurate results.

Another critical factor in the stability of riprap installations is the quality control that is used to insure that the specified rock size and gradation is being used. With the large stone diameters that are typical of such installations, it is very difficult to make precise measurements of the rock characteristics (i.e., D_{50} or W_{50} and gradation). Obviously, if the design specifications are not complied with, the riprap blanket will be prone to failure.

For the case of grouted rock, the grout is the only agent holding the rock matrix together. If the grout begins to crack, there is a possibility that some loosened stones could be swept away. Also, there is a possibility that buoyant forces might tend to "pop" the grout blanket if sufficient water flows or seeps under the blanket.

Since the grouted rock blanket is a rigid mass, there would also exist the potential for this mass, or slab, to break if scour or piping forces were to remove the finer soil particles that form the embankment slope upon which the blanket is placed. Certainly a <u>filter blanket</u> would be a mandatory requirement to prevent piping for <u>all</u> three of the bank protection methods presented in the COE report.

Gabions provide the flexibility that does not exist in a grouted rock blanket. Accordingly, gabions can adjust to deformations in the embankment slope. The primary caution in using gabions would focus on the potential for abrasion or debris impacts to break the wire used for the baskets. If the wire were to break, the stone contents of the baskets would be subject to removal by the high velocity flow.

As a fourth alternative to bank protection products, the author would suggest the possible use of soil cement. This product has been used extensively on flood control projects in Arizona and has successfully withstood very severe flood conditions.

Application in Arizona

The author is not aware of any specific alluvial fans in Arizona where the design guidelines presented in the COE report have been used. However, the elevation of structures on compacted fill is a common practice in riverine floodplain environments.

6.8 Two-Dimensional Flow Models

A common problem in conducting floodplain analyses on alluvial fans results from the expansion of flows (both water flows and mudflows) across those portions of the fan surface where no entrenched channel exists to carry such flows. These conditions can most accurately be simulated by two-dimensional (2-D) flow models.

Four 2-D models (RMA-2, Schamber, Link-Node, and Diffusion Analogy) are briefly described by Hamilton, MacArthur, and Li (Simons, Li & Associates, Inc. 1988). Although these models have not been perfected for alluvial fan analyses, three of the models show potential for further research and development that might lead to a 2-D model that could produce realistic simulations of expanding flow across alluvial fans.

The following subsections present brief discussions of these three models. The "link-node" model is excluded because it was judged to be a poor candidate for an alluvial fan environment.

6.8.1 RMA-2 Model

This model was developed at the U.S. Army Corps of Engineers' Hydrologic Engineering Center in Davis, California, in cooperation with Resource Management Associates.

The model is described as utilizing the complete two-dimensional momentum and continuity equations to simulate free-surface, steady or unsteady flows. The modeling approach employs a finite-element grid that is capable of using individual grid elements that may alternate between wet and dry conditions during passage of a flood hydrograph. SLA (1988) reports that there are presently no known applications of this model on alluvial fans.

6.8.2 Schamber Model

In response to severe mudflow damage that occurred in the spring of 1983 along a 30 mile length of the Wasatch Front Mountains in Utah, the Hydrologic Engineering Center was requested by the Omaha District Corps of Engineers to develop a practical method for analyzing mud and debris flow hazard areas. The results of this research, which were published in 1988 (U.S. Army Corps of Engineers, Omaha District), produced a computer model which was composed of three submodels to analyze the movement of mudflows from a steep mountain canyon out onto an alluvial fan. These three submodels are used to perform the following operations:

1. *estimate mudflow volume* – This operation is based on a mathematical relationship between drainage area and total debris flow volume. This relationship was developed on the basis of actual measurements of mudflow volumes that resulted from the 1983 event along the Wasatch Front Mountains. Accordingly, it should not be used in other geographical locations if topographic and geologic conditions differ from the Wasatch Front, Utah.

2. *generate mudflow hydrograph at the canyon mouth (alluvial fan apex)* – The mudflow hydrograph is determined as a function of the mudflow volume estimated in Step 1, the channel geometry of the canyon, and the physical properties (viscosity, yield strength, unit weight, etc.) of the soil–water mixture. A dam break analogy is used as an initial boundary condition for the one–dimensional modeling process that is used to develop the mudflow hydrograph.

3. *route the mudflow onto the alluvial fan surface* – The movement and expansion of the mudflow onto the fan surface is simulated

by a 2-D model which uses the mudflow hydrograph from Step 2 as an upstream boundary condition. Topographic data is provided to the model in the form of a "macro-element" grid drawn onto a topographic map. The corner of each grid element is given an x-y coordinate and an elevation.

A computer generated, finite-element grid is then expanded onto this predefined geometric surface. When the mudflow hydrograph is routed through the finite-element grid, the model records the lateral extent of mudflow movement, as well as the depth and velocity at each node point during the peak discharge of the event. Such data can be used to define hazard areas in terms of depth and velocity contours.

When combined with the FEMA procedure discussed in Section 6.1 of this report, the Schamber model becomes an important tool in producing much more accurate hazard delineations for alluvial fans that are prone to frequent mudflow events. The Corps' report (1988) divides alluvial fans into three regions which exhibit different types of hazards. These regions are identified as the:

1. *mudflow region*, which is closest to the apex and exposed to a high risk of mudflow damage; the

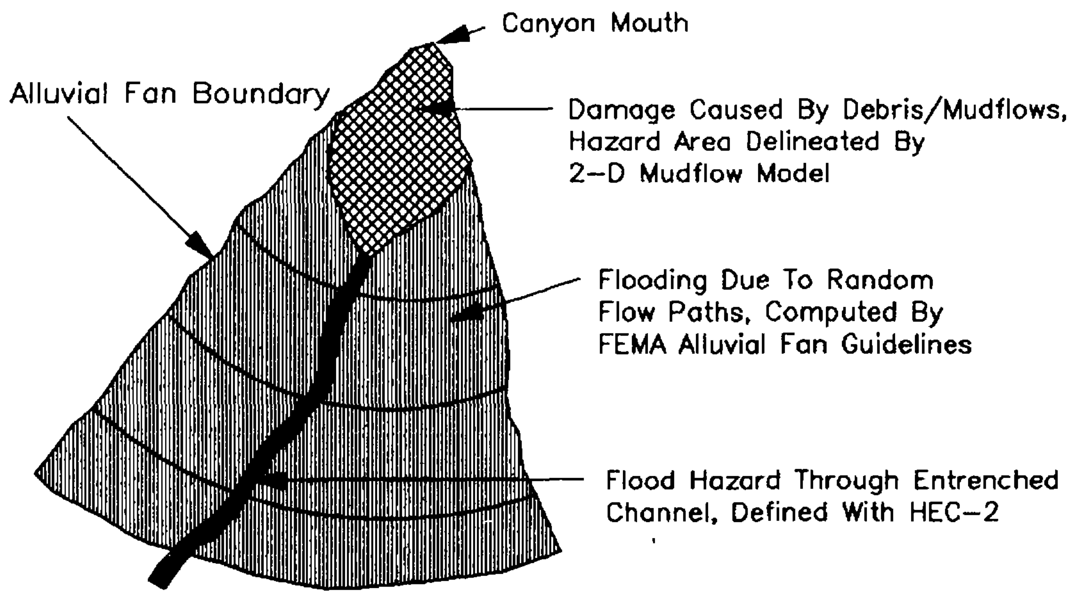
2. *transition region*, which is downstream of the mudflow area, but still subject to severe sediment deposition; and the

3. *clear water flood region*, which is on the lower portions of the fan where an approximate equilibrium condition exists between the sediment transport capacity of the flowing water and the sediment supply to the water. Depending on the existence of natural or

manmade channels, flood depths and velocities may be estimated for this region by application of the FEMA method or conventional riverine hydraulic models such as HEC-2.

Figure 6.3 illustrates a hypothetical fan that exhibits different hazard regions and possible methods for quantifying the hazard potential within each region. It should be emphasized that not all alluvial fans are alike. Accordingly, the type and magnitude of hazard will vary from one fan to another.

Figure 6.3
Typical Flood Hazard Delineation
For An Alluvial Fan



Even though the Schamber model was originally developed for mudflow analyses, it would seem to provide a good foundation for further research and development for eventual application to water flows across alluvial fans.

6.8.3 Diffusion Model

Technical literature contains several references to diffusion modeling. SLA (1988) cites a diffusion model, called DHM, that was developed by Hromadka (1985). For the purpose of this technical discussion, the author obtained excerpts from a drainage study, prepared by NBS/Lowry (1987), which used a diffusion model developed by Dr. G.L. Guymon. It is believed that the Guymon model is a modification of the previous work undertaken by Hromadka.

The diffusion model applies the two-dimensional flow equations to a user-specified grid that is superimposed onto the area to be studied. Each cell formed by this grid must be square and must be identical in size. Input data for each cell describes boundary conditions (for linking to adjacent cells) and an average elevation and Manning's roughness value. Cell boundaries can also be coded to prevent flow from moving through a boundary.

Diffusion equations are developed for each cell, and cell boundary, comprising the grid. The solution of these equations provides the discharge, velocity, and depth of flow across each of the four sides of every cell in the grid network. By providing a flood hydrograph as an input parameter, the path and hydraulic characteristics of a flood can be traced through a drainage network.

The model is also capable of routing runoff from precipitation that falls directly onto the grid network, i.e., this runoff is in addition to that being input to specific grid cells in the form of a runoff hydrograph. However, the model is not capable of computing infiltration losses. Accordingly, the rain falling directly onto the grid network must be input in the form of "effective" rainfall that has already been adjusted for infiltration losses.

This data is supplied in the form of coordinates describing a hyetograph (effective rainfall versus time).

The most serious disadvantage of this model would appear to be the requirement to use a constant grid spacing (cell size). For watersheds that have complex or abrupt topography, this might require an unreasonably large number of cells to get an accurate definition of the surface contours.

This diffusion model was recently applied to the Upper East Fork of Cave Creek in Maricopa County, Arizona (NBS/Lowry 1987). This watershed is part of an alluvial fan that is characterized by a network of numerous small rills that have very little hydraulic capacity. Due to uncertainties in estimating the flow path across this fan, a four square mile grid network, with 660-foot square cells, was developed for application of the diffusion model. TR-20 was used to develop a flood hydrograph for input to the diffusion model.

The results of this modeling process provided a schematic of the water movement across the fan surface, as well as depth, velocity, and discharge data for each of the grid network cells. This information was ultimately used for an evaluation of several drainage plans for the study area.